SOME STRUCTURAL RELATIONSHIPS OF TEXAS BLACKLAND SOILS

with Special Attention to Shrinkage and Swelling

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CONTENTS

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in cooperation with

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SOME STRUCTURAL RELATIONSHIPS OF TEXAS BLACKLAND SOILS, WITH SPECIAL ATTENTION TO SHRINKAGE AND SWELLING[1]

R. M. Smith[2]

INTRODUCTION

The purpose of this study is to increase the understanding of structural behavior in fine-textured soils, especially as they occur in the Blacklands of Texas. The starting point is natural soil structure as observed in the field under variable land use or treatment. Since shrinkage and swelling with changes in moisture constitute an outstanding physical characteristic of Blackland soils, (figure 1) this has been the primary factor considered. An attempt has been

Figure 1. Contrasting structures of Houston Black clay surface soil: Mechanically puddled versus natural, loose cultivation.

[1]This work is cooperative between the Western Soil and Water Management Research Branch, Soil and Water Conservation Research Division, Agricultural Research Service, United States Department of Agriculture, and the Texas Agricultural Experiment Station.

[2]Soil Conservationist and Superintendent, Blackland Experiment Station, Temple, Tex. Most of the laboratory results were obtained by Laboratory Assistants R. C. Henderson, Jr., and Floyd Robinson. The cooperation of W. R. Elder, Soil Scientist, Soil Conservation Service, United States Department of Agriculture, and of several other representatives of SCS operations involving field sampling, observation, and interpretation is gratefully acknowledged.

made to find out how much and under what conditions different soils or materials shrink or swell. By means of mechanical alterations, chemical treatments, and theoretical considerations some evidences have been brought out as to the causes of observed or measured results. Texture, lime content, exchangeable cations, organic matter, and clay mineral type are the main factors which have been considered along with mechanical treatments and moisture, expressed in terms either of volume or of moisture tension.

It is hoped that readers who are interested primarily in soil and water conservation or soil management will gain useful information about soil structure in relation to the practical solution of farm problems. At the same time, this study may suggest to technical specialists some new lines of investigation that are of major interest and that might lead to improved conservation farming operations.

LITERATURE REVIEW AND BACKGROUND

Houston Black clay and closely related Blackland Prairie soils have been grouped with other deep, dark-colored clay soils of the world under the general name "Grumusol" (23).[3] An outstanding characteristic of Grumusols, by definition, is a high coefficient of expansion and contraction on wetting and drying. This characteristic results in wide, dry-weather cracks and the process of profile rejuvenation known as "self-swallowing," which produces the typical "buffalo-wallow" or "gilgai" microrelief of grasslands in the area. Under cultivation the surface is disturbed so frequently that persistent sinks and "wallows" usually are not formed; but regardless of land use, a quantity of surface soil moves downward in shrinkage cracks at various intervals determined by rainfall, tillage practices, livestock, and other factors.

Katz (12) credits early botanists with the following definition of swelling: "A solid is said to swell when it takes up a liquid, whilst at the same time (a) it does not lose its apparent (microscopic) homogeneity; (b) its dimensions are enlarged; (c) its cohesion is diminished: instead of hard and brittle, it becomes soft and flexible".

In the case of Houston Black Clay and similar soils, a vigorous disruptive action is associated with swelling. As water is taken up, the volume increases, cohesion is diminished, and any unconfined mass or unit of the soil exhibits warping, cracking, exfoliation, and various degrees of disruption. When the soil is confined on all sides, swelling may be accomplished with no apparent loss of homogeneity.

Recognition of the "expanding lattice" of Montmorillonite (9) had a strong influence on concepts of swelling of colloidal clay. The reported spacing of unit sheets for 3 specimens at moisture contents above 25 or 30 percent was between 18 and 22 Å compared to 15.2 to 15.7 Å at air dryness and 11.0 to 11.5 Å when dried at 100° C.

3/ Numbers in parentheses refer to Literature Cited, at end of report.

Marshall (20) has stated that "swelling, strictly regarded, is an osmotic property of the clays" and is obviously related to interparticle forces. Baver and Winterkorn (2) indicated that swelling of soils and clays is more complicated than swelling of substances used by Katz (12) as the basis for certain thermodynamic calculations, although they stated there is reason to believe that the orientation of molecules on the surface of clays as a result of the electrical properties of both the liquid and the surface may follow the laws developed by Katz. The results of Baver and Winterkorn (2) indicate that intermicellar, or surface, phenomena are responsible for most swelling of clays. They found that the K^+-saturated colloids behaved more like the divalent clays or H^+ than like Na^+ or Li^+. Also, Winterkorn and Baver (30) showed that sorptive behavior of different soil colloids is related to the structure of the colloidal complex, the amount and nature of the exchangeable cations, and the electrical properties of the sorbed liquid. Lutz (18) reported that bentonite showed more swelling than Putnam colloid, which swelled more than Iredell; and that Davidson showed no appreciable swelling regardless of exchangeable cations. The low-erosive nature of Davidson was believed to be related to the nonhydrated condition and high flocculation.

Kelly (13), referring to the osmotic effect of dissociated ions, pointed out that swelling of Na-saturated montmorillonite samples from different sources, or even from different types of bentonite, is not always proportional to the base-exchange capacity. Other characteristics of the clay, obviously, are involved. Marshall (19) suggested that oriented coagulation and other reactions such as swelling should be quite different for beidellite, with charges caused by substitution of Al^{3+} for Si^{4+} in the outer tetrahedral sheets, than for montmorillonite, with charges arising from substitution of Mg^{2+} for Al^{3+} in the middle aluminum sheet. He reasoned that the degree of dissociation of the montmorillonite would be greater than that of beidellite having the same charge.

Referring to the structure of clay soils in relation to swelling, Page (24) emphasized the time factor under field conditions. During the growing season, he pointed out, the soil may not have an opportunity to approach complete swelling. As evidence that external surface swelling is important, even with expanding lattice clays, Page indicated that maximum internal expansion to 20 Å or more is achieved by relative humidities of 90 percent, whereas relative humidities of more than 98.5 percent exist at moisture contents below the range of plant wilting. Starting with a dry Ca-system and using water vapor, Barshad (1) stated that internal swelling seems to end with a relative humidity of 50 to 60 percent.

If there were no internal attractive forces, as indicated by Marshall (20), osmotic forces would be expected to disperse a clay colloid throughout any volume; but results all seem to indicate a tendency for clay to occupy a limited rather than an infinite volume. He described this tendency as corresponding to a zone of "thixotrophy," which indicated that in the absence of agitation internal forces hold the system together in opposition to osmotic forces. With one sodium bentonite, Mattson (21) calculated that the internal attraction corresponded to a negative osmotic pressure of approximately 0.02 atmosphere.

Variations in the shrinkage coefficients of natural soils of similar colloid percentage led Hardy (7) to the conclusion in 1923 that different soil colloids possess different and specific moisture characteristics. A simple method of portraying soil volume changes associated with variations in water content was developed by Haines (6). This method, as applied to puddled, saturated clays or soils, was used to distinguish "normal shrinkage" from "residual shrinkage." Normal shrinkage represents volume changes equal to water losses, with no air in the system. Residual shrinkage, on the other hand, was defined as the volume change occurring after air enters the system and volume change becomes less than volume of water loss. Lauritzen (15) reasoned that differences between capillary or film water and water held in the lattice structure may account for residual shrinkage as defined by Haines.

Volume changes in relation to moisture content of natural soil clods and of puddled blocks of Blackland soil were measured by Lauritzen and Stewart (16). The method used was to coat the soil unit with a thin layer of paraffin and to determine the volume by water displacement at intervals as the soil dried slowly through the paraffin. Differences noted among samples indicated that shrinkage was dependent on the manner in which the moisture was associated with the soil material and pore space in the soil mass. Volume change per unit of water loss was believed to reach a maximum at moisture contents approximating the wilting coefficient. Lauritzen (15) also reported that dry apparent specific volume (or porosity) of Blackland soil clods was invariably higher than that of plastic blocks prepared from the same material. On this basis he suggested that dry apparent specific volume of natural soil compared with dry apparent specific volume or blocks formed from puddled soil may be useful as a measure of soil structural development.

Shrinkage characteristics of natural Houston Black clay and Austin clay were determined by Johnston and Hill (11) and illustrated by field photographs. Houston Black clay showed greater shrinkage than Austin clay. Reduced moisture was found adjacent to soil cracks in the field, indicating moisture loss through the cracks. Wetting and drying of large soil clods in the field was said to be essential to formation of excellent seedbeds.

When sand was mixed with Houston Black clay, Lauritzen (15) reported that the range of shrinkage was narrowed but the character was about the same. Alfalfa meal mixed with puddled Houston Black clay caused residual shrinkage (air entry) to begin at a higher moisture content. The shape of the shrinkage curve for the high-organic-matter mixture (1 part alfalfa and 2 parts soil) resembled the curve for soil with natural structure before puddling.

Aggregate stability created in silty soils by albumin, fats, and other substances as reported by McCalla (22) was believed to be associated with slow wetting and reduced swelling. Laws (17) indicated that water-soluble-silicate application to Houston Black clay caused some decrease in the tendency for swelling and shrinkage. In considering effects of organic matter, Page (24) suggested that structural units once formed in the soil

would readily disappear and recombine with others in the soil if not stabilized. This stabilization is thought to be the chief role of natural organic matter as well as of synthetic, long-chain soil additives, such as "krilium." Davidson and Page (3) found that organic matter removal (3 percent) and iron removal (0.2 percent) both increased the swelling pressures of the clay fraction of Houston Black clay by the method that they devised and tested. With 4 different soils studied, Miller clay showed lowest shrinkage of natural clods and lowest swelling pressure; Houston Black clay and Beaumont clay showed highest shrinkage and high swelling pressure; and Lufkin clay showed intermediate shrinkage but highest swelling pressure. Higher organic matter and incomplete exchange of all Ca ions were suggested as possible reasons why Houston Black clay did not show more swelling pressure than Lufkin clay. X-ray diffraction determinations indicated that Houston Black clay was highest in montmorillonite. However, the specific nature of the montmorillonite may be involved, since Foster (5) found a variation in "free swelling" of from 21 to 66 cc. per gram for different specimens of montmorillonite, the higher values being associated with lower octahedral substitution.

One of the most comprehensive field studies of soil shrinkage and cracking was reported by Hardy and Derraugh (8). They classified soil cracks on a basis of width, depth, and configuration. Although water loss is the cause of shrinkage cracks, they pointed out that rate of drying is also important, as well as nature of the colloidal minerals, organic matter including the degree of humification, and the occurrence of salts. The functions of cracks were described as including the following: (a) Drainage, (b) weathering, (c) self-mulching, (d) aids to tillage, (e) channels for roots (moist faces), and (f) infiltration.

Stirk (28) concluded that although shrinkage is a prominent characteristic of many clay soils with massive structure, it cannot be relied upon to compensate for their low permeability and poor aeration when irrigated. The influence of the cracks, he said, is greatest when the soil water content has been reduced to levels not always practicable with continuous irrigation. Moreover, even with deep cracks which might allow water to reach great depths, the moisture distribution would be very uneven.

In working with molded clay blocks from several soils, Holmes (10) found that between pF 2 and pF 5 all water-content change was accompanied by an equal change in volume of the pore space if a small hysteresis in wetting was neglected. The moisture tension-water content relationship of some natural clay aggregates was very similar to that of blocks made from the same material. Thus, the moisture tension-water content relationship in the clay was determined by its swelling property rather than by the pore-size distribution.

EXPERIMENTAL MATERIALS AND METHODS

Most of the soil samples studied were Houston Black clay or Austin clay from the southern Blackland area of Texas. Various depths in soil

profiles were selected, as well as soils with varied cropping and management history. Selected samples of alluvial soils of the Reddish Prairie, near Brownwood, Tex., samples of heavy-textured soils of the Gulf Coast Prairie near Victoria, Tex., and a few other soils, and soil materials were included to provide comparative data as described in connection with results.

It has been shown that Houston Black clay is rather consistent in certain characteristics (14). The 0.002-mm. clay in 5 complete profiles to a 100-inch depth varied from 40 to 68 percent. Cation exchange capacity varied from 25 to 69 m. e. per 100 grams. In the surface 18 inches the range was from 58 to 77 m. e. Calcium carbonate equivalent of the surface varied from 5 to 32 percent. Montmorillonite was shown by x-ray diffraction studies to be the predominate mineral in the clay fraction. Other minerals recognized were calcite, quartz, kaolinite, and illite. The presence of an amorphous constituent was suggested by x-ray diffraction as well as by differential thermal analyses.

Cultivated Houston Black clay used in these studies contained 2.5 to 3.0 percent organic matter and 15 to 30 percent calcium carbonate equivalent. Native grass samples contained 5.0 to 5.3 percent organic matter and 30 to 50 percent calcium carbonate. Eroded Austin clay contained 1.9 percent organic matter and 50 percent calcium carbonate. Reddish Prairie samples from Brownwood contained 2.0 to 3.0 percent of organic matter, a trace of free carbonate, and no measurable sodium.

Lumps or clods,[4/] cores, and unconsolidated aggregates of soils were studied, depending on the object and nature of measurements. When lumps were formed artificially, the soil was presoaked for 4 hours or more and then mixed thoroughly at plastic consistency until all appearances of structure were eliminated. Desired lumps were formed by hand at or slightly below the sticky point. Most of the porosity, bulk density, and total volume determinations were made with 4 or more replicate lumps or clods which varied in dry weight from about 5 to 150 gm. In most cases the weights were between 15 and 50 grams. Bentonite and some separated clay samples shattered so much during drying that fragments for density and porosity measurements weighed as little as 2 gm.

Air space within lumps was determined by saturation with a nonpolar liquid at any moisture content, as described elsewhere (27). Varsol cleaning fluid-specific gravity about 0.77-has been used.[5/] Bulk density was determined by paraffin coating and weighing in air and in water. Specific-gravity measurements of selected samples were made with a pycnometer. The only sample which varied greatly from a specific gravity

4/ These terms are used interchangeably to indicate any mass of the soil which is handled as a unit.

5/ Mention of a product is not to be construed as an endorsement of it by the U. S. Department of Agriculture over those not mentioned.

of 2.65 was the Wyoming bentonite. The average value obtained for bentonite was 2.38. When porosity was measured with nonpolar liquid and bulk density by paraffin coating, specific gravity could be calculated. With soil of a known specific gravity, either porosity or bulk density could be calculated whenever one or the other was to be measured.

Moisture retention at 15 atmospheres was determined with a standard pressure-membrane-extraction apparatus; lower pressure-retention values were determined on ceramic units.

Laboratory swelling volume determinations on soil lumps were made by wrapping soil lumps in cotton, placing them in 3-inch-long cylinders on fine sand, covering with fine sand to a depth of 1/2 to 1 inch over the top of each lump, and wetting by maintaining free water in the sand at about 1/2 inch below the lump. When water intake was complete, the lump was removed from the sand and its volume was determined, either by paraffin coating or by the nonpolar liquid method.

Slaking in the laboratory was accomplished by quick, complete submersion in water, followed by siphoning off of excess water and slow air drying to desired moisture contents.

Water-drop slaking was carried out by placing lumps on 1/4-inch-mesh screen over a Buchner funnel with a base of saturated blotting paper under a tension of about 40 cm. of water column. Then water drops of 0.1 gm. each were released above the lumps at 1 drop per second from a height of 60 cm. until the soil was all forced through the screen onto the blotting paper. Next, the soil was drained under a 40-cm. tension, was removed from the funnel and broken into lumps of suitable size for porosity measurements by the standard method.

Soil-setting volume was determined as follows. Approximately 20 gm. of dry soil was soaked in distilled water for 4 hours or more. Then the soil in about 100 cc. of water was stirred for 5 minutes in a high-speed stirrer. The suspension was transferred to a 250-cc. graduate, diluted to 250 cc., and allowed to stand until the soil settled. The settling volume was read as cubic centimeters of settled soil in the graduate. Readings were repeated until the volume was stable.

EXPERIMENTAL RESULTS

Precision and Methods of Presentation

Typical variation among replicates by the nonpolar-liquid method of determining porosity is illustrated by the data in table 1. Bentonite lumps showed more variation than soil samples. Bulk density of bentonite lumps by paraffin coating indicated somewhat higher porosity than the average values from Varsol[6] determinations. Limited penetration of

6/ See footnote 5.

Table 1.--Percent porosity of replicate lumps as determined by the standard procedure with a nonpolar liquid

Description of sample	Replicate	Moisture content	Total porosity of individual lumps
		percent	percent
Houston Black clay, puddled	1	44.8	54.6
	2	44.9	54.4
	3	45.5	54.8
	4	45.8	55.1
	5	45.3	54.8
	6	45.1	54.8
	Average	45.2	54.7
	Standard deviation		0.24
Houston Black clay, puddled	1	Oven-dry	23.6
	2	do	23.4
	3	do	23.6
	4	do	24.5
	5	do	24.8
	6	do	23.7
	Average		23.9
	Standard deviation		0.57
Austin clay, lime-free	1	79.7	68.0
	2	79.3	67.9
	3	82.1	69.2
	4	79.9	68.1
	Average	80.3	68.3
	Standard deviation		0.60
Austin clay, lime-free	1	12.4	28.8
	2	13.2	29.7
	3	12.9	30.3
	4	13.1	29.9
	Average	12.9	29.7
	Standard deviation		0.63
Houston Black clay, lime-free, plus 50 me/100 of Na +	1	83.8	69.5
	2	81.9	69.0
	3	84.9	69.9
	4	90.3	71.2
	Average	84.3	69.9
	Standard deviation		0.95
Wyoming bentonite	1	Oven-dry	4.6
	2	do	12.2
	3	do	6.7
	4	do	7.6
	5	do	8.0
	6	do	7.6
	Average		7.8
	Standard deviation		2.53

Varsol[6] into extremely fine pores that are accessible to water would account for such discrepancies. With bentonite and similar colloids the specific gravity measured probably depends upon the degree of dispersion into ultimate particles. Thus it is difficult to separate the absolute specific gravity from the method of determination.

A standard shrinkage curve has been used to present many of the results obtained with natural soil or with packed or puddled specimens. A typical curve is illustrated in figure 2. The method is essentially the same as that used by Haines (6) in his work with puddled soil blocks.

In figure 2 the curve between points for "wet" soil and "moist" soil is essentially a straight line with volume change equal to the volume of water loss. The term "normal shrinkage,"[7] as usedby Haines (6), applies, except for the fact that the soil samples contained considerable air, whereas Haines visualized normal shrinkage as applicable to a 2-phase, solid-liquid system with no air present.

Between moist and oven-dry conditions shrinkage was less than the volume of water loss. For these soils Haines' term "residual shrinkage" might apply below about 30 cc. of water per 100 cc. of solids.

Detailed shrinkage curves for 3 soils are presented in figure 3. Since each point is an average of 6 replicate lumps and moisture intervals are closely spaced, the nature of typical curves is well defined.

Houston Black clay shows a somewhat closer approach to normal shrinkage throughout the moist and wet range than the other two soils. There appears to be some tendency for the Houston Black clay and Austin clay curves to flatten in the wet extreme. Porosity and bulk density of a number of samples at air dryness (about 5 to 10 percent) and at oven dryness (105° C.) were essentially equal.

Figure 4 was prepared so that the shrinkage graphs may be quickly and conveniently used. With soil specific gravity of 2.65, which is near the mean for most samples studied, cubic centimeters of total soil volume can be converted directly to bulk density. Also, bulk density can be converted to porosity and vice versa.

Natural Soil Profiles

For soils of the Blackland Prairie area, as well as for certain other soils that have similarity of texture with depth, it seems normal for porosity to decrease with depth in the profiles. This natural tendency

6/ See footnote 5.

7/ The term "normal shrinkage" will be used in this discussion to include all cases where gross-volume change is essentially equal to water loss.

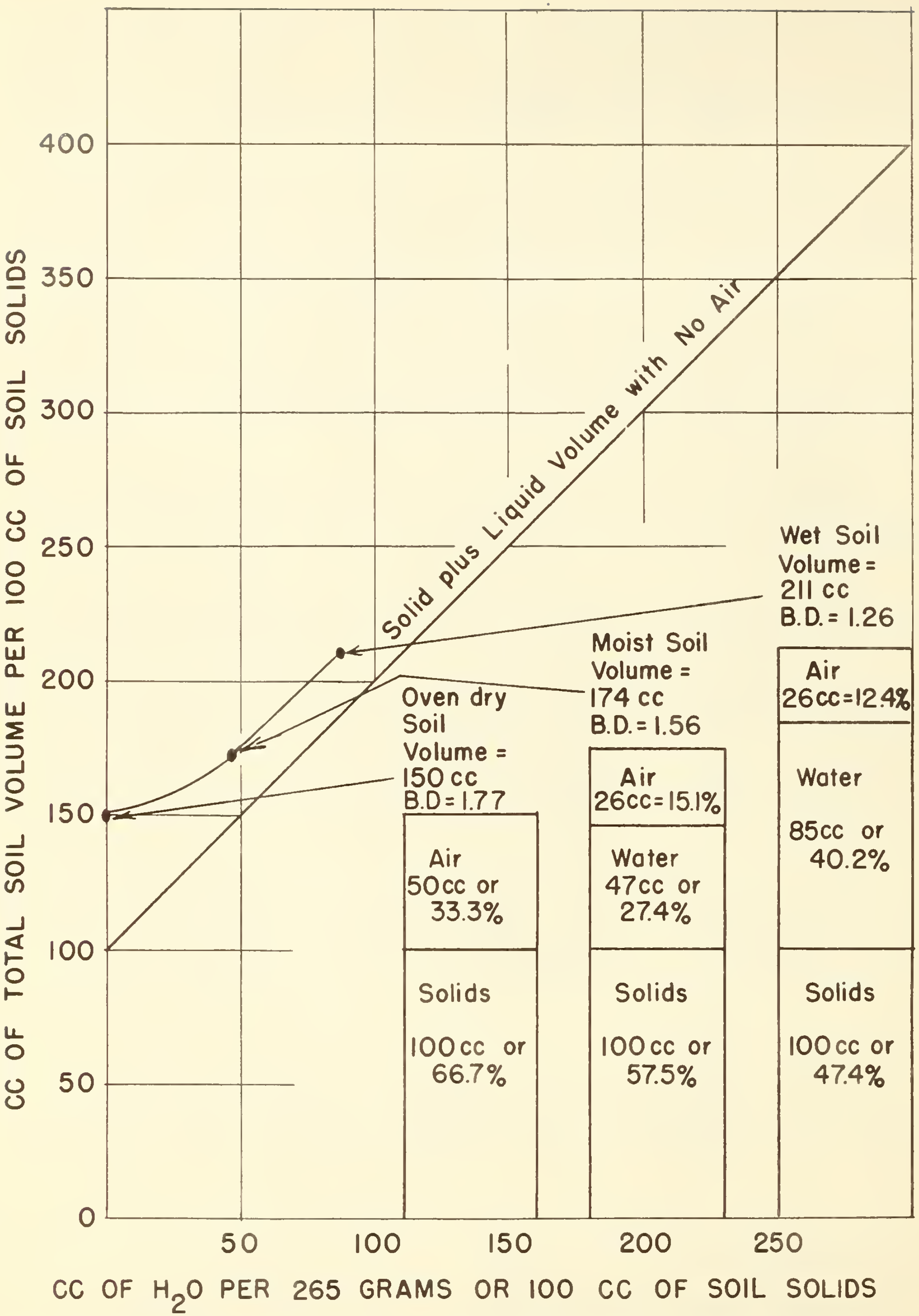

Figure 2.--Houston Black clay shrinkage curve based on 265 gm. or 100 cc. of dry soil solids, with block diagrams to illustrate the solid, liquid, and air volumes at 3 points on the curve.

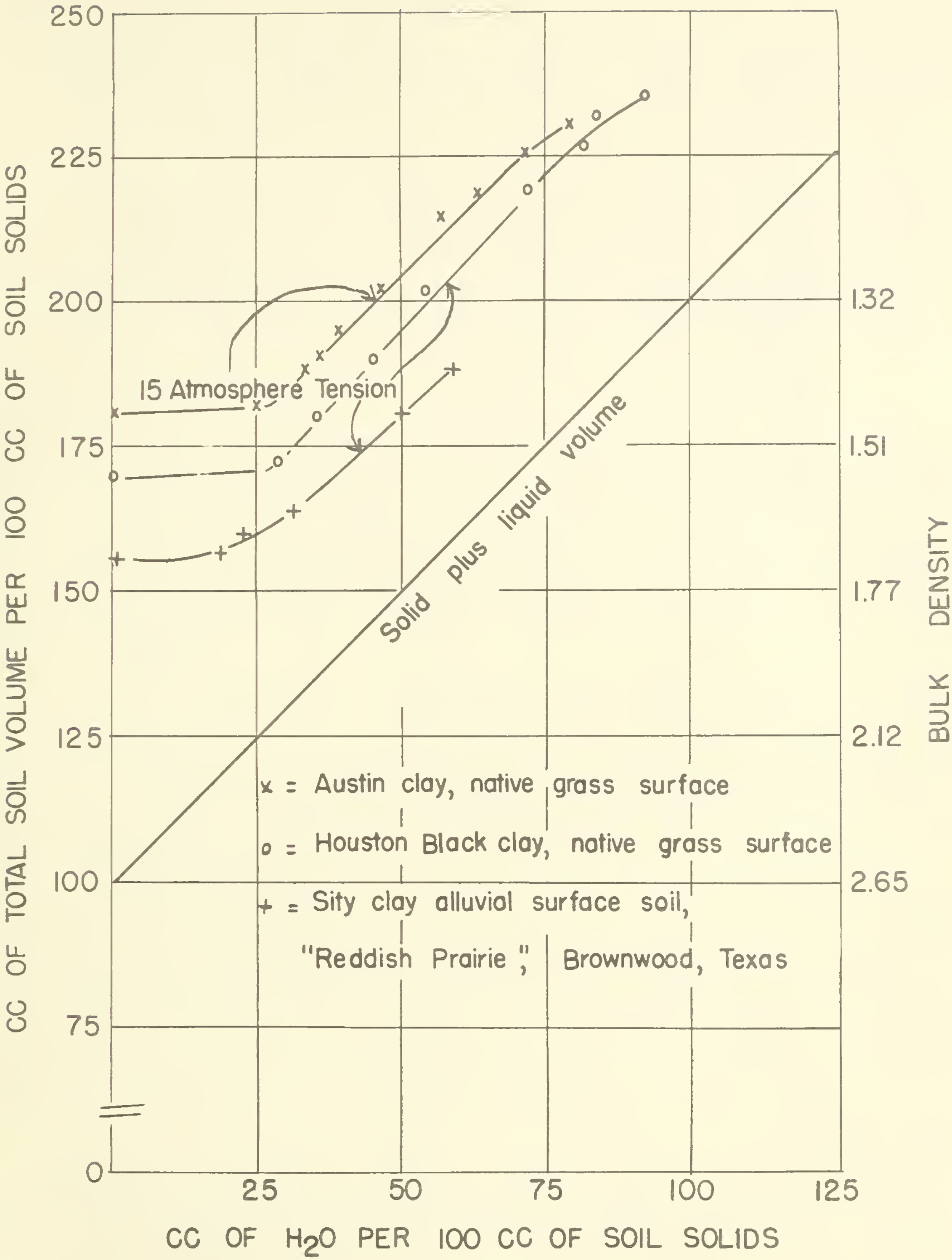

Figure 3.–Shrinkage curves for natural lumps from 3 soils by the paraffin-coating method. (Each point is an average for 6 replicate lumps.)

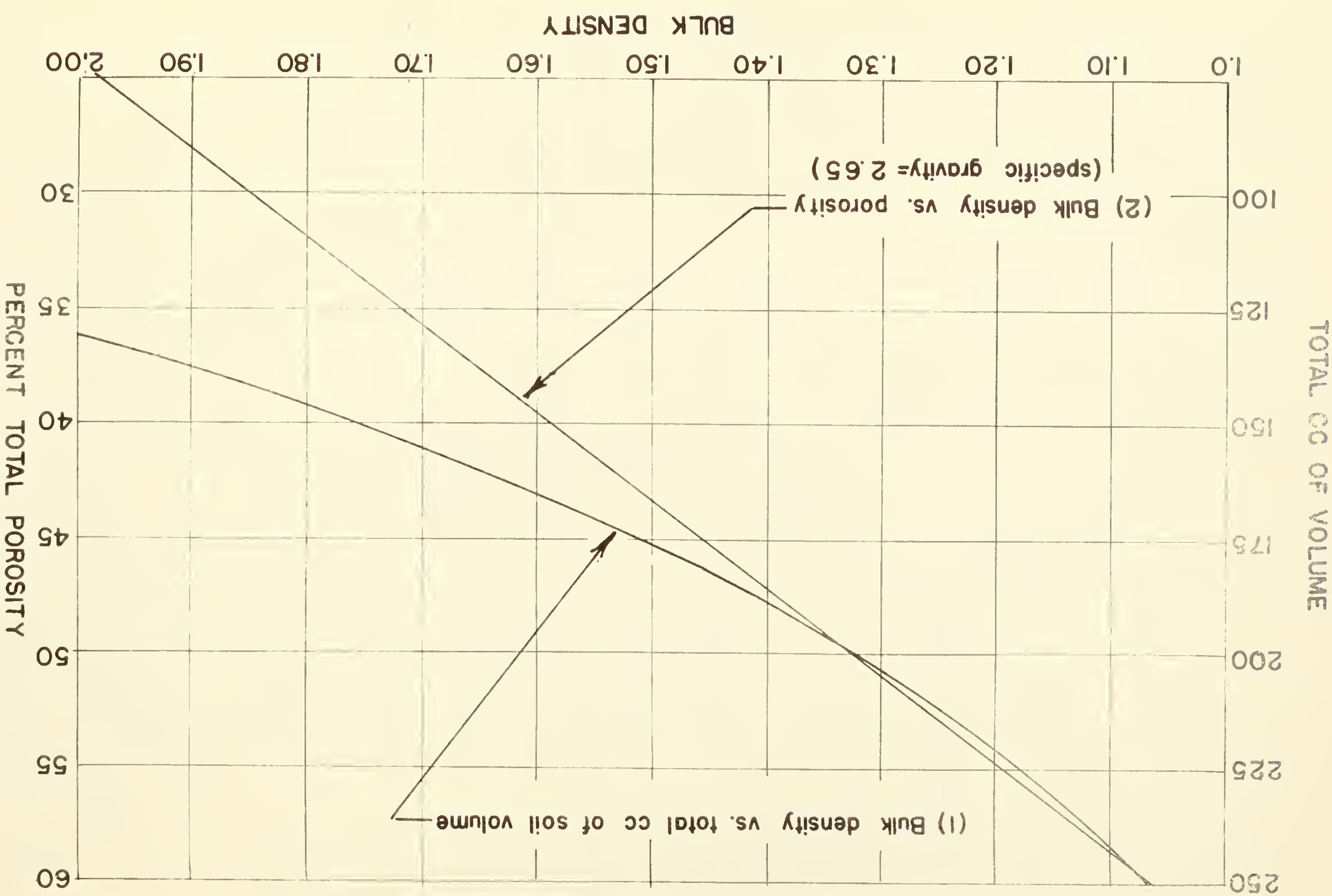

Figure 4.--Relationship between (1) bulk density and cubic centimeters of total soil volume as plotted on standard shrinkage curves; and (2) bulk density and porosity.

is illustrated in figures 5, 6, 7, and 8. It should be noted that the greatest difference in every case is between the surface sample and that taken immediately below. In order to detect porosity differences, it is necessary to make the measurements at comparable moisture contents. In figure 5, for example, the samples of the surface layer had less porosity at oven dryness than naturally moist samples of the densest layer at the 18- to 24-inch depth.

Even with a sandy loam soil, as illustrated in figure 9, the moisture contents must be comparable or the wrong impression of porosity may be obtained. As sampled in the field, the 16- to 24-inchdepth was slightly more moist and more porous than samples from 12 to 16 inches. However, at oven dryness the porosities are reversed and the curves suggest that at comparable moisture the deeper depth should be considered denser or less porous than the shallower depth.

Compaction or Puddled Layers

Figures 10 and 11 illustrate soil layers below the immediate surface which are less porous than the next layers below them in the soil profiles. By comparison of porosity trends with depth in normal soil profiles, these layers seem to represent abnormalities caused by use. A similar situation at the immediate soil surface is illustrated by figure 12. Heavy grazing of fescuegrass pasture when wet has resulted in elimination of most of the air space as judged by that found for the same soil in an adjoining ungrazed pasture.

Artificial puddling of native-grass surface soil accounts for the contrast shown in figure 13. The natural soil contained about 50 cc. of air space per 100 cc. of solids when moist or wet, whereas after puddling the air space was 2 cc. This artificially puddled native-grass soil contained less air throughout all moisture ranges than the overgrazed fescuegrass-pasture surface soil of figure 12.

Maximum Packing Density

Figure 14 shows that when Houston Black clay was packed at 20 percent moisture, greater density or less porosity was achieved than at 14 percent or 28 percent moisture. At 14 percent the soil particles were too dry to combine and adjust to a high density. At 20 and 28 percent moisture the porosity and density were controlled by the moisture content. Packing eliminated essentially all air, at both moisture contents. Additional packing at 28 percent was not possible without elimination of water.

As shown by the curves of figure 14, the soil at all moisture contents showed shrinkage as a result of drying. At oven dryness, there was little difference in porosity or density between the samples packed at 20 and at 28 percent moisture, whereas the samples packed drier, at 14 percent, were considerably more porous.

(text continues on p. 24)

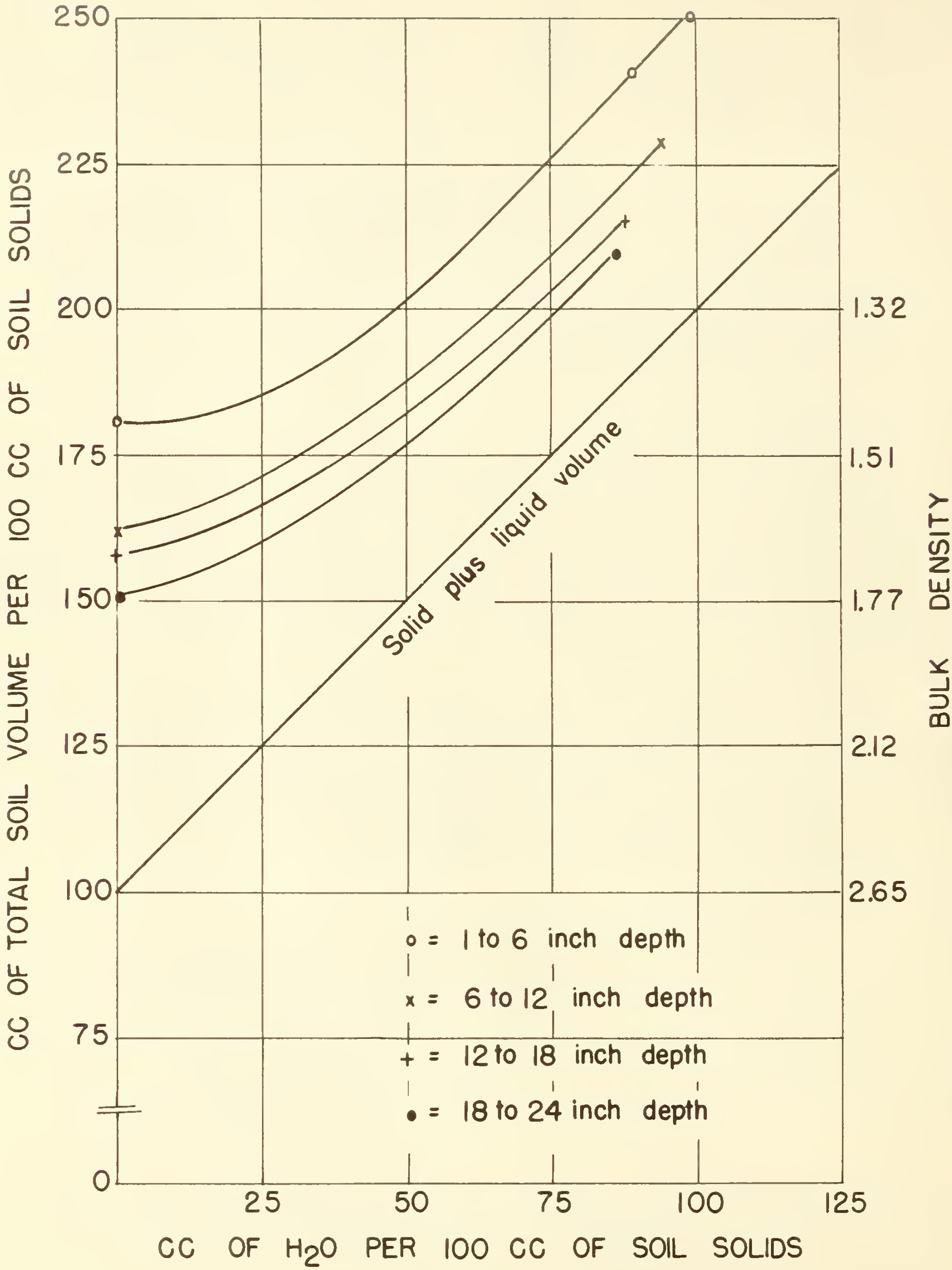

Figure 5.--Shrinkage curves for natural soil lumps from 4 depths in hand cultivated runoff plot 20, Houston Black clay.

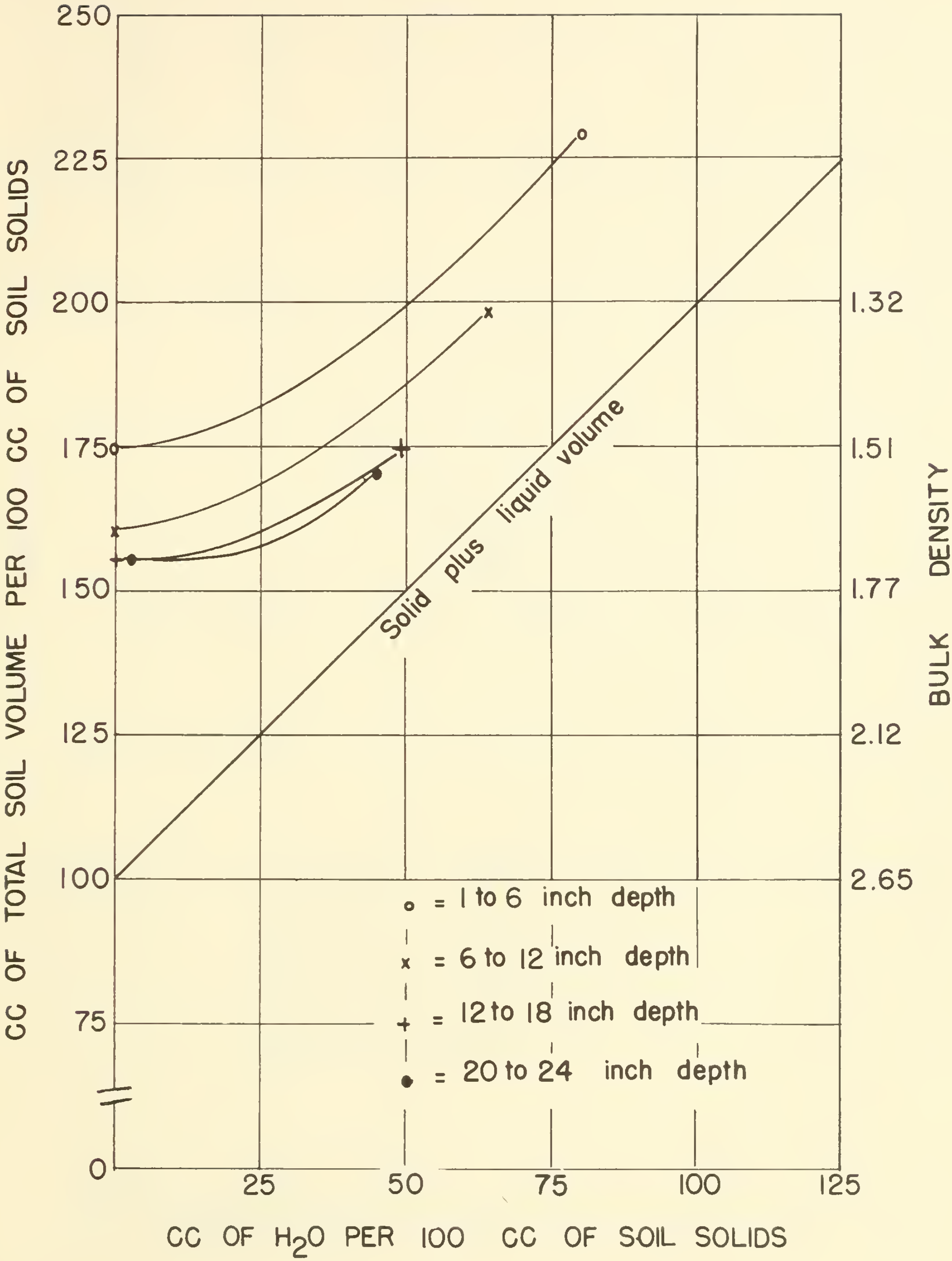

Figure 6.--Shrinkage curves for natural soil lumps from 4 depths of Houston Black clay, native grass.

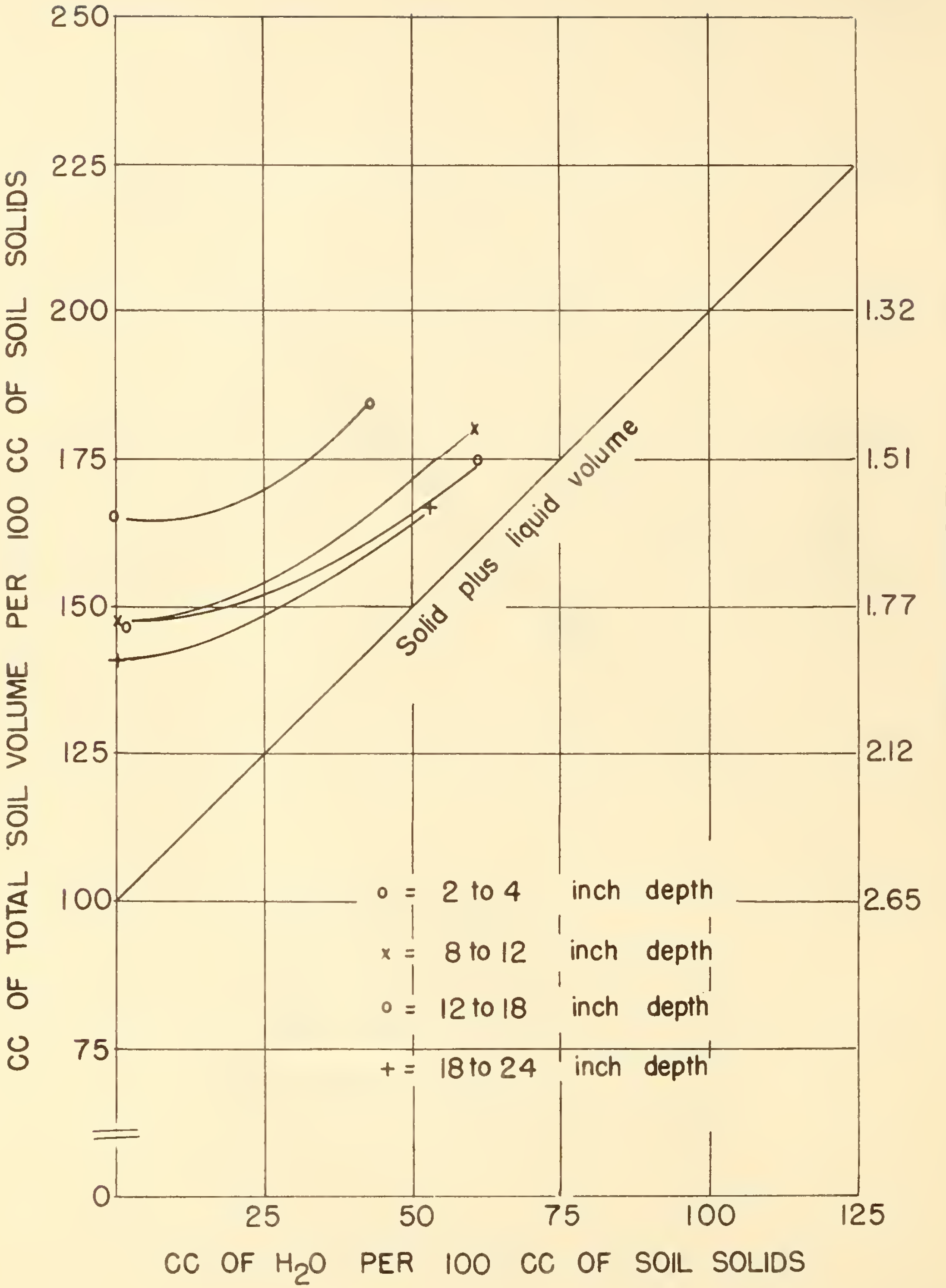

Figure 7.--Shrinkage curves for natural lumps from 4 depths of a brown, silty clay alluvial soil, "Reddish Prairie," Brownwood, Tex.

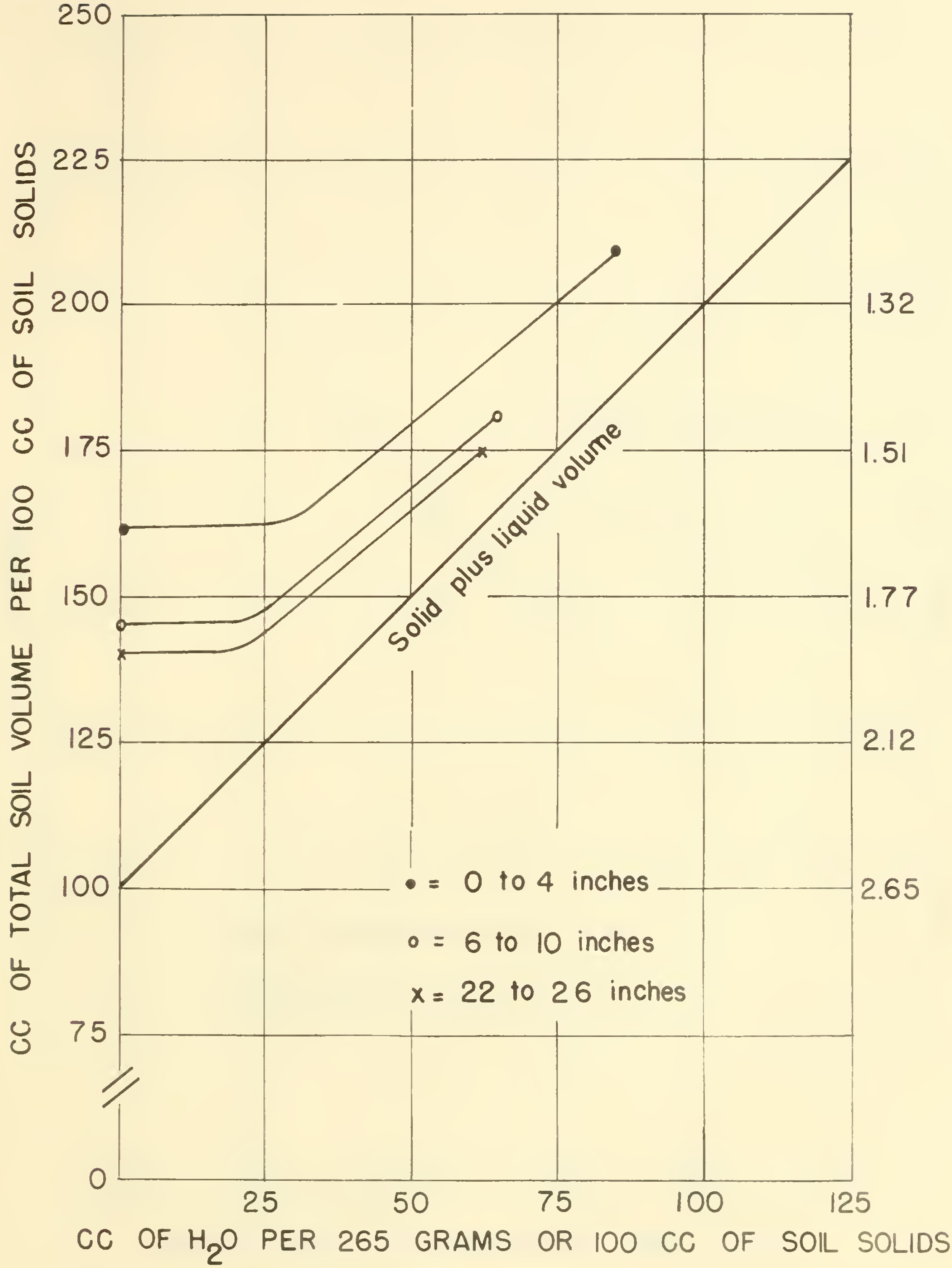

Figure 8.--Shrinkage curves for natural clay soil lumps, Gulf Coast Prairie, native grass.

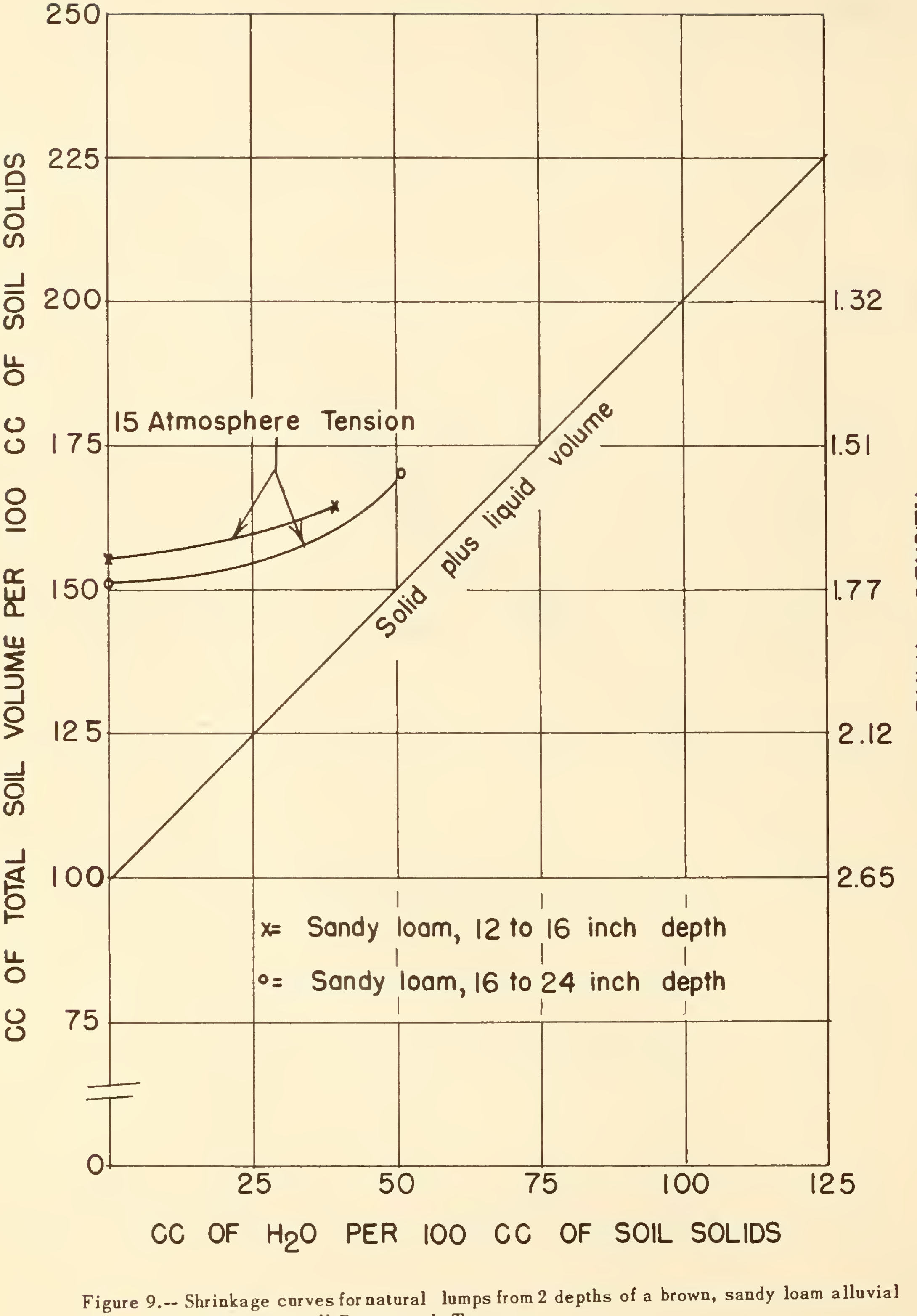

Figure 9.-- Shrinkage curves for natural lumps from 2 depths of a brown, sandy loam alluvial soil, "Reddish Prairie," Brownwood, Texas.

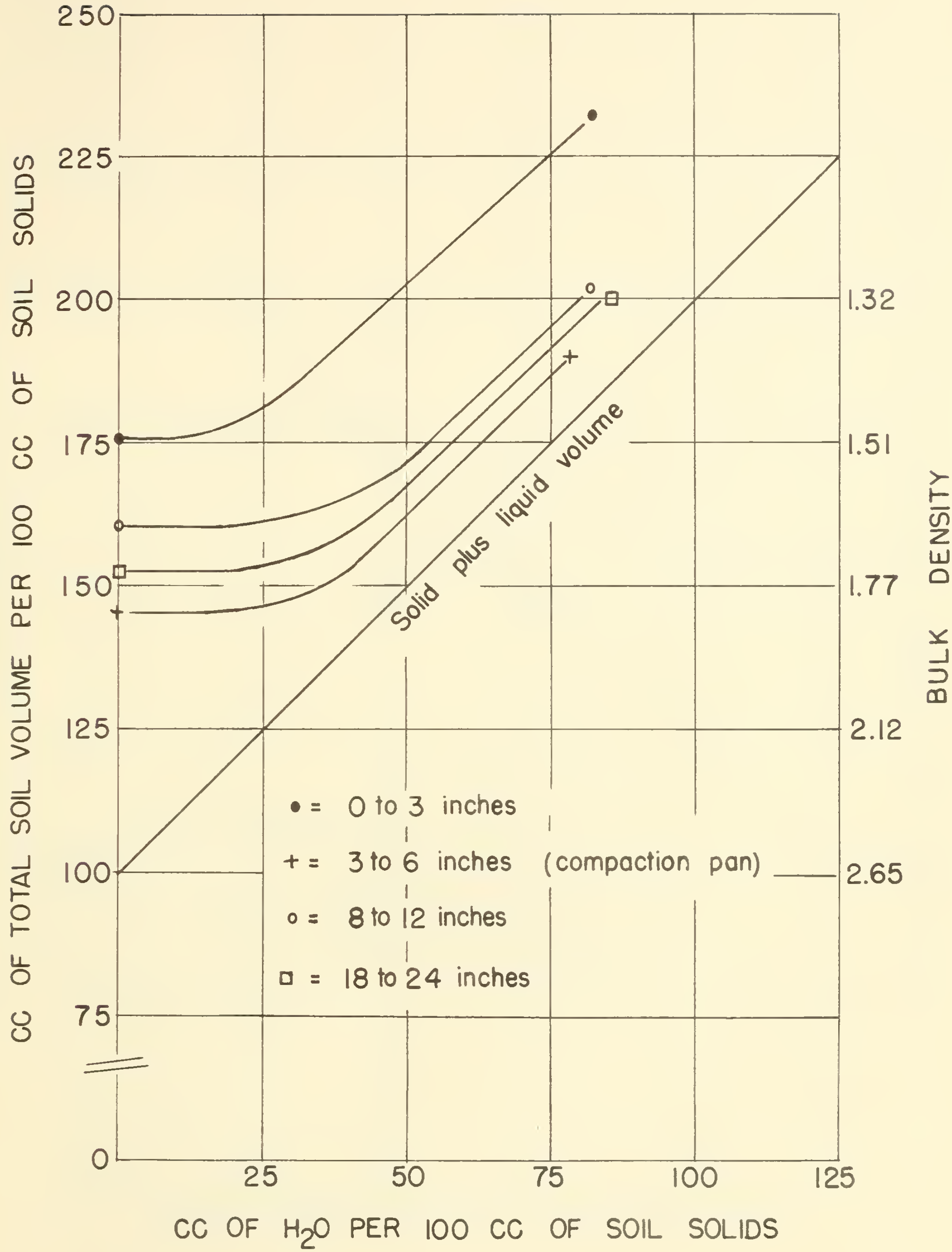

Figure 10.--Shrinkage curves for natural lumps from 4 depths of cultivated Houston Black clay, illustrating an apparent "compaction pan."

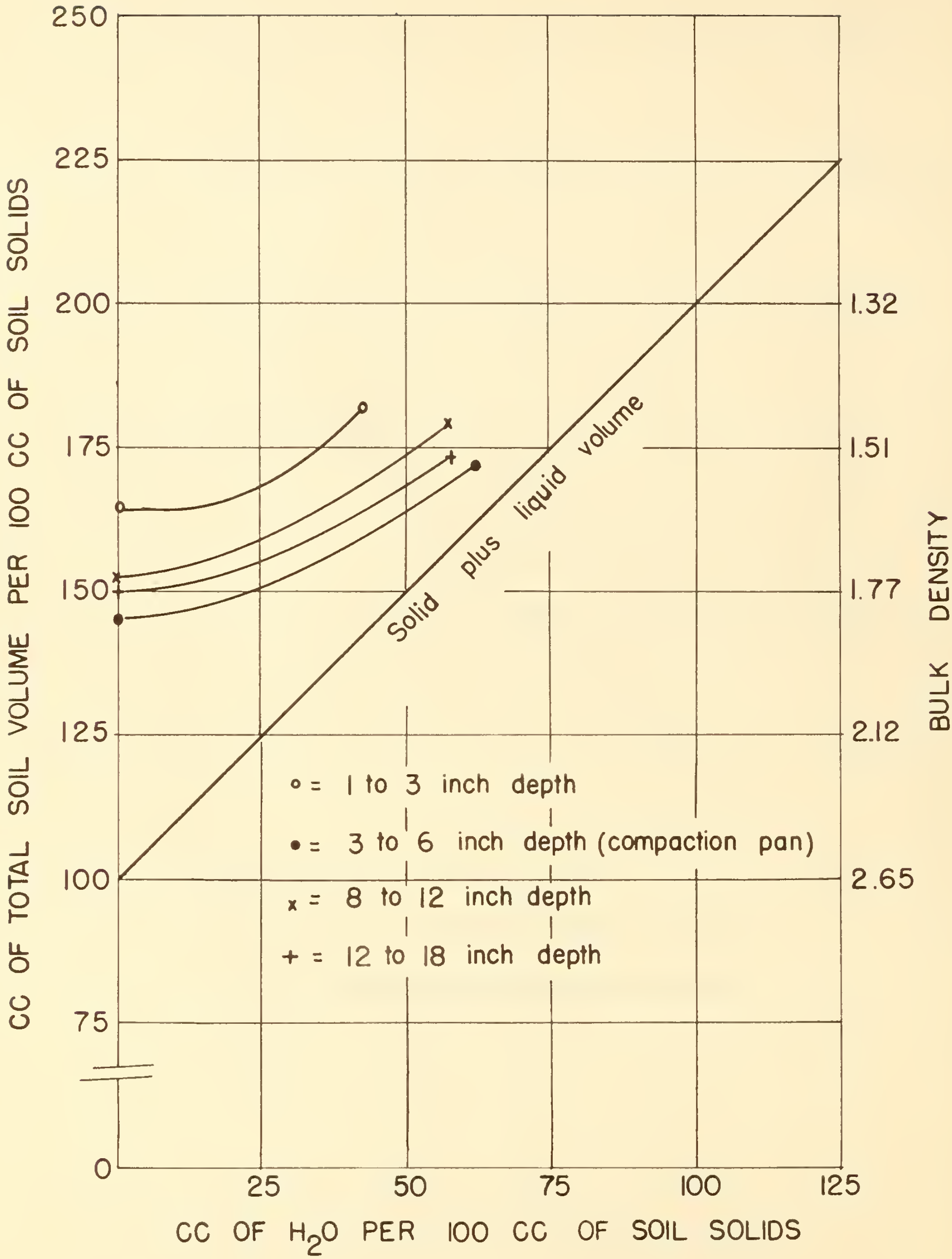

Figure 11.--Shrinkage curves for natural lumps from 4 depths of a silty clay alluvial soil, "Reddish Prairie," Brownwood, Tex., illustrating an apparent "compaction pan."

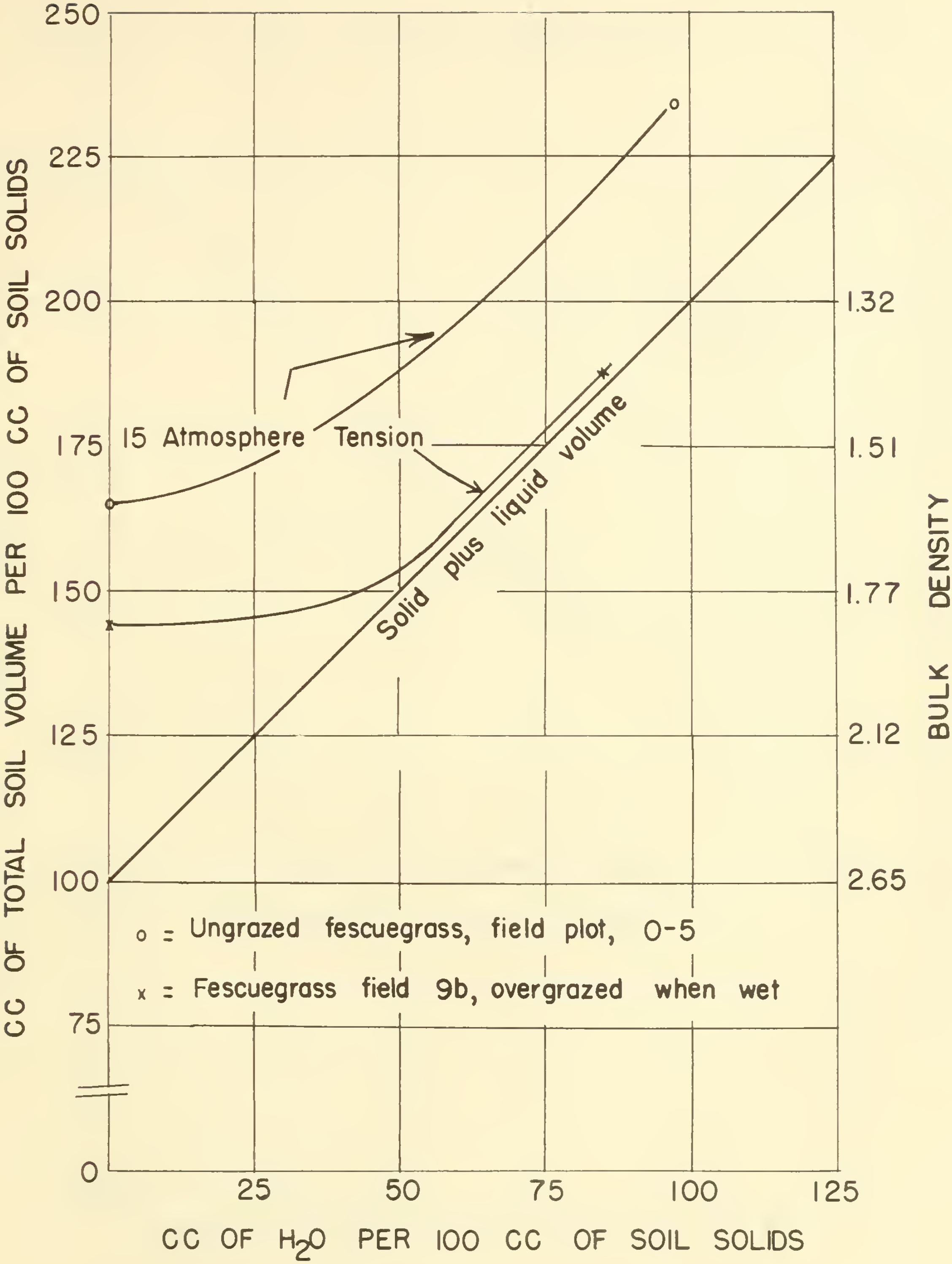

Figure 12.--Shrinkage curves for natural surface soil lumps from ungrazed fescuegrass versus fescuegrass overgrazed when wet, both Houston Black clay, adjacent fields, Temple, Tex.

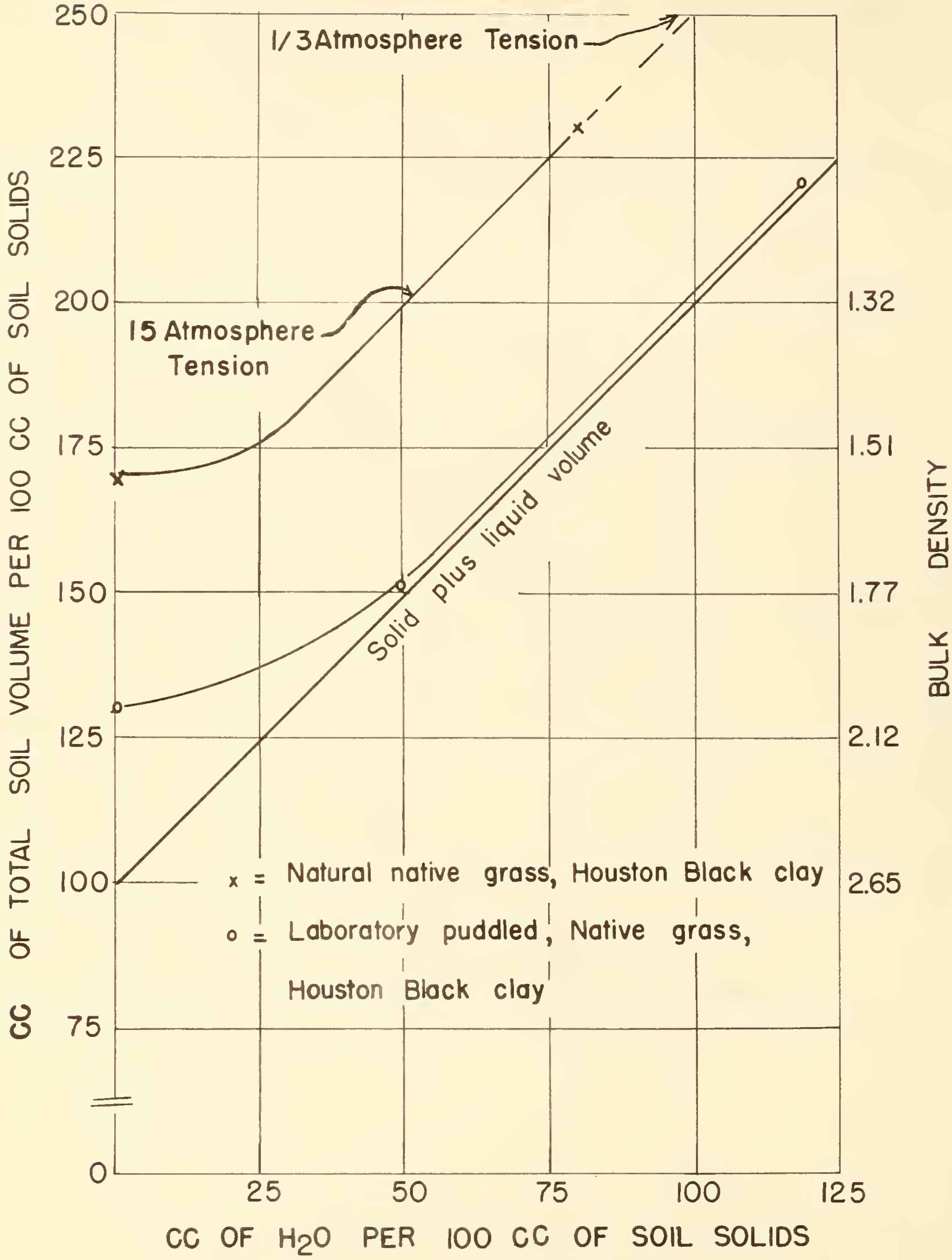

Figure 13.--Shrinkage curves for lumps of Houston Black clay surface soil, natural soil versus laboratory puddled, native grass pasture.

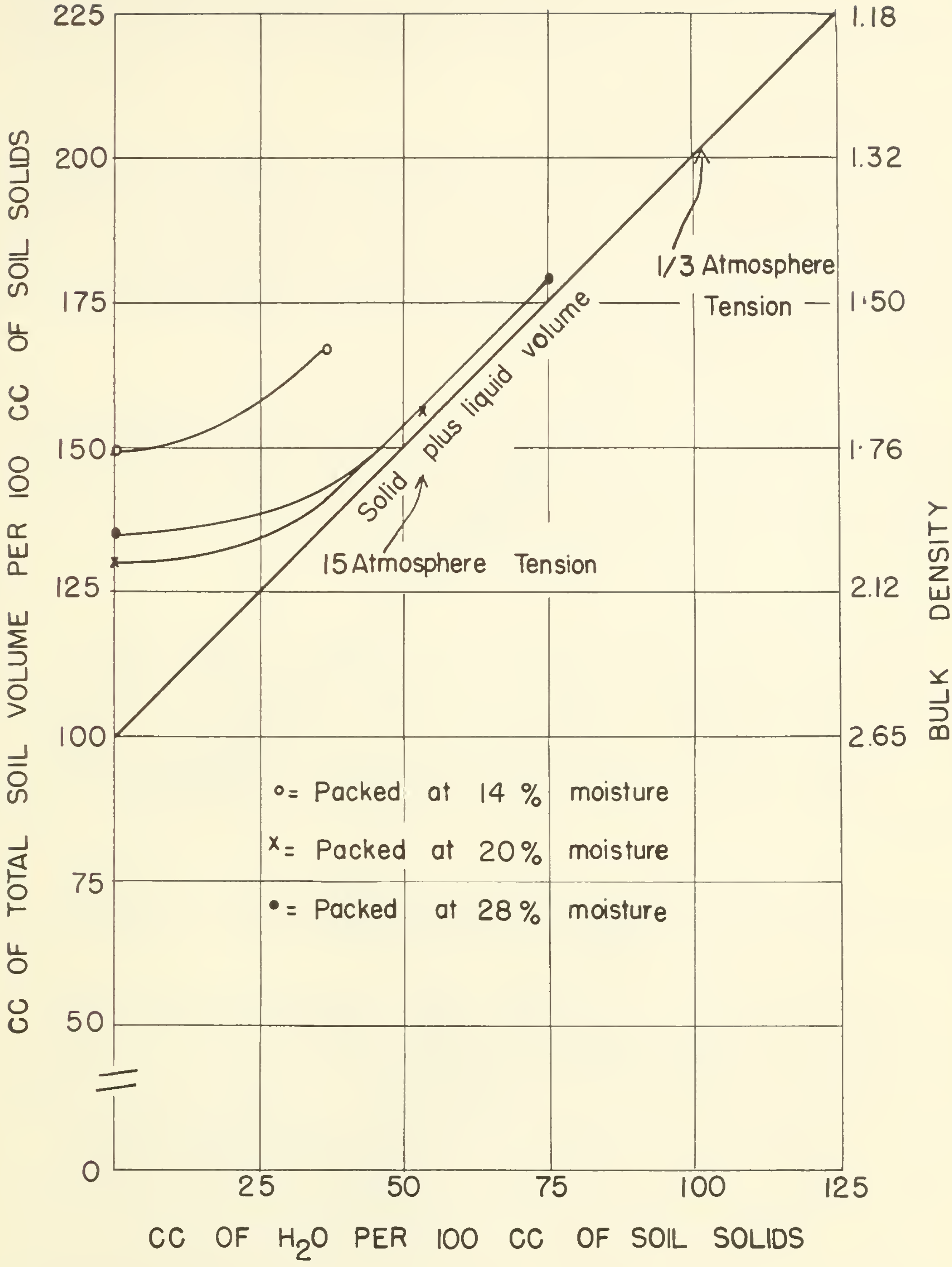

Figure 14.--Shrinkage curves for "Proctor" laboratory packed Houston Black clay, cultivated surface soil samples, packed at 3 different moisture contents.

It is evident that high-swelling and shrinking soil cannot be packed to high density when wet because the water of swelling prevents further volume reduction after essentially all air has been eliminated. Maximum density is achieved only by drying and shrinkage.

Lime and Organic Matter Removal

As shown by figure 15, lime or organic matter removal had only a small influence on shrinkage of Houston Black clay surface soil. Dry volume was slightly lower than for the same soil with lime and organic matter present. Free carbonate, or lime, was removed by prolonged soaking in HC[1] of less than 0.1 N strength until the soil maintained a pH of about 4. Chlorides were then removed by repeated washing with distilled water until no chlorides could be detected with a silver-nitrate test. Organic matter was removed with H_2O_2.

The somewhat higher maximum moisture content of the lime-free soil probably is significant. Almost all air was removed by puddling, either with or without lime. Final porosity of dry soil was 23 percent with no lime and 25 percent with lime. Other samples showed the same relationship, the lime-free soil being slightly more dense in each case. The minimum porosity without organic matter was 21 percent.

Cation Effects

Addition of Na^+ (50 m. e. per 100 gm.) caused a higher moisture content at the sticky point where puddled lumps were formed, and also slightly higher maximum density at oven dryness (figure 16). Porosity of oven-dry lime-free Houston Black clay with 50 m. e. of Na^+ per 100 gm. was 15 percent compared with 23 percent for the lime-free soil without Na^+. Another sample of Houston Black clay had 13 percent porosity at oven dryness with 50 m. e. of Na^+ per 100 gm. versus 17 percent when saturated with H^+.

As shown in figure 17, neither K^+ nor Fe^{+++} addition caused any definite differences from lime-free, H^+-saturated soil. If anything, the porosities were slightly higher.

When organic matter was removed before dispersion with Na^+, the resulting soil did not shrink to a density as high as that of dispersed soil with organic matter present (figure 18). This was true for both the 10 m. e. and the 50 m. e. Na^+ per 100 gm. of soil. Without Na^+ the minimum porosity was 21 percent; with 10 m. e. of Na^+ it was 25 percent; and with 50 m. e. of Na^+ it was 30 percent. A different sample with lime and organic matter removed showed minimum porosity of 23 percent; with 10 m. e. of Na^+ the porosity was: First run, 32 percent, second run, 26 percent.

The 0.002-mm. clay fraction was separated from Houston Black clay by sedimentation following removal of lime and organic matter and dispersion with Na^+ and was formed into lumps. These lumps had maximum volumes, by the standard method of plotting, of 414 and 421 cc., respectively, for

(text continues on p. 29)

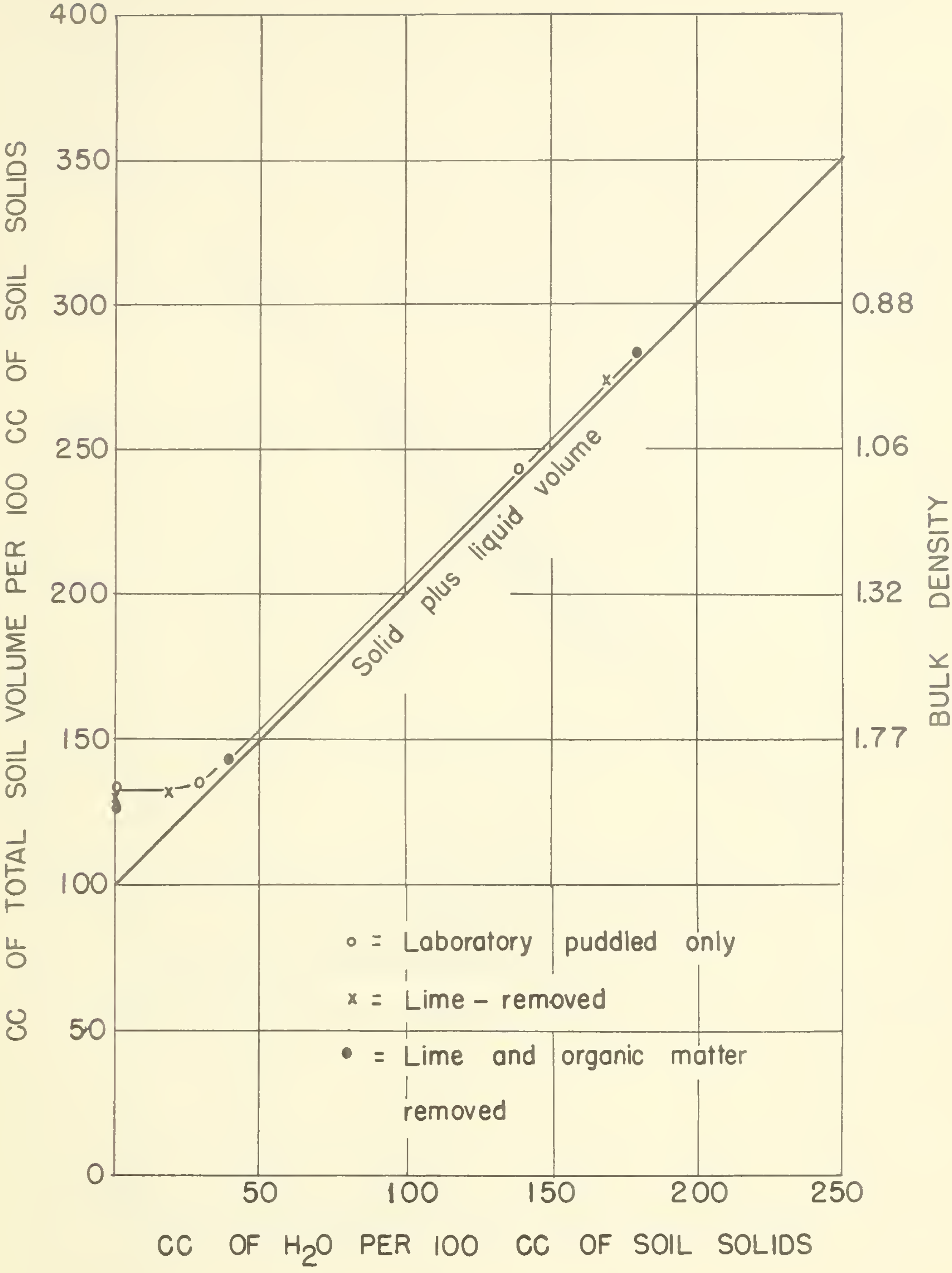

Figure 15.--Shrinkage curves for hand formed lumps of Houston Black clay cultivated surface soil.

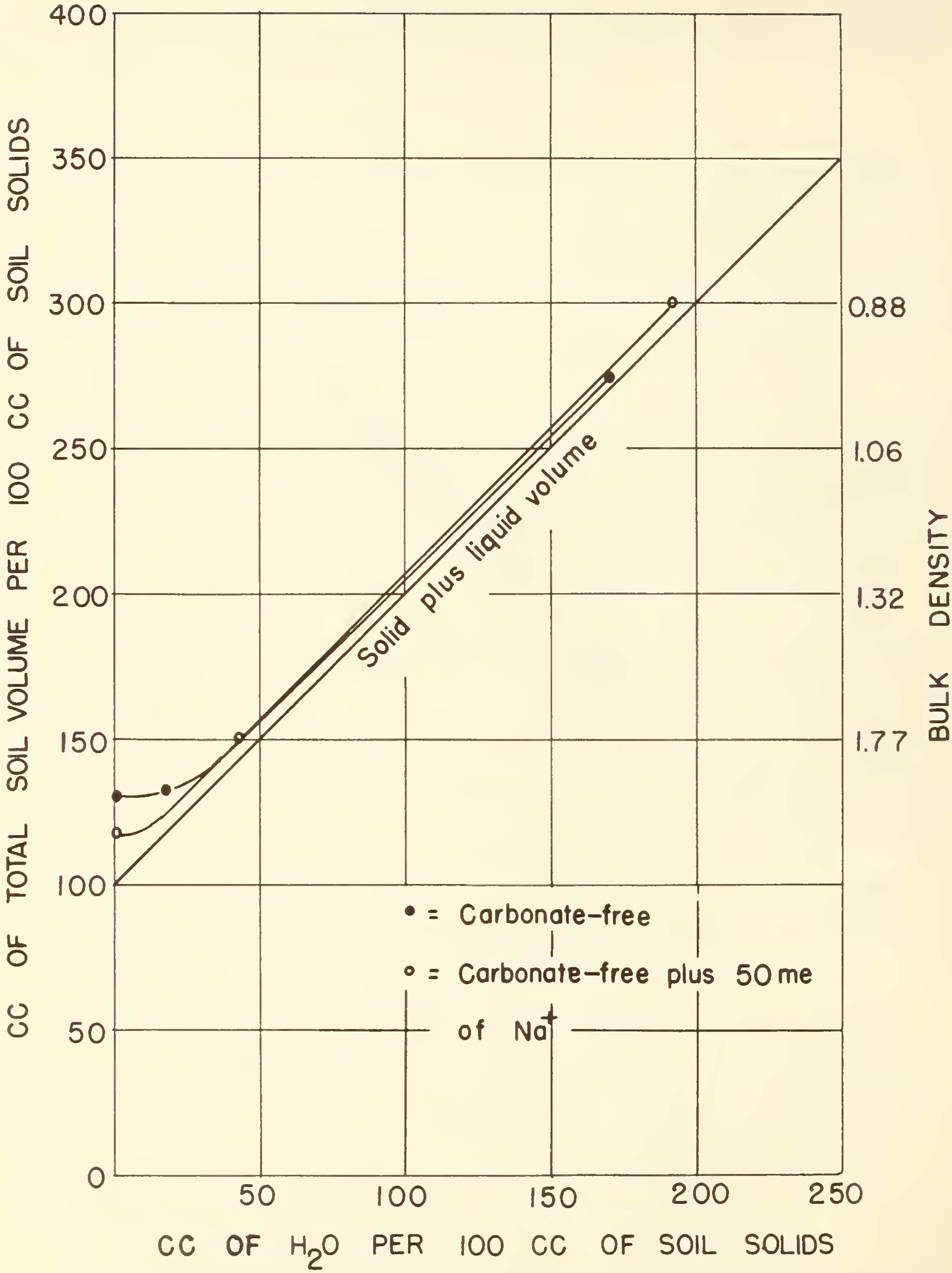

Figure 16.--Shrinkage curves for Houston Black clay, puddled lumps formed from cultivated surface soil.

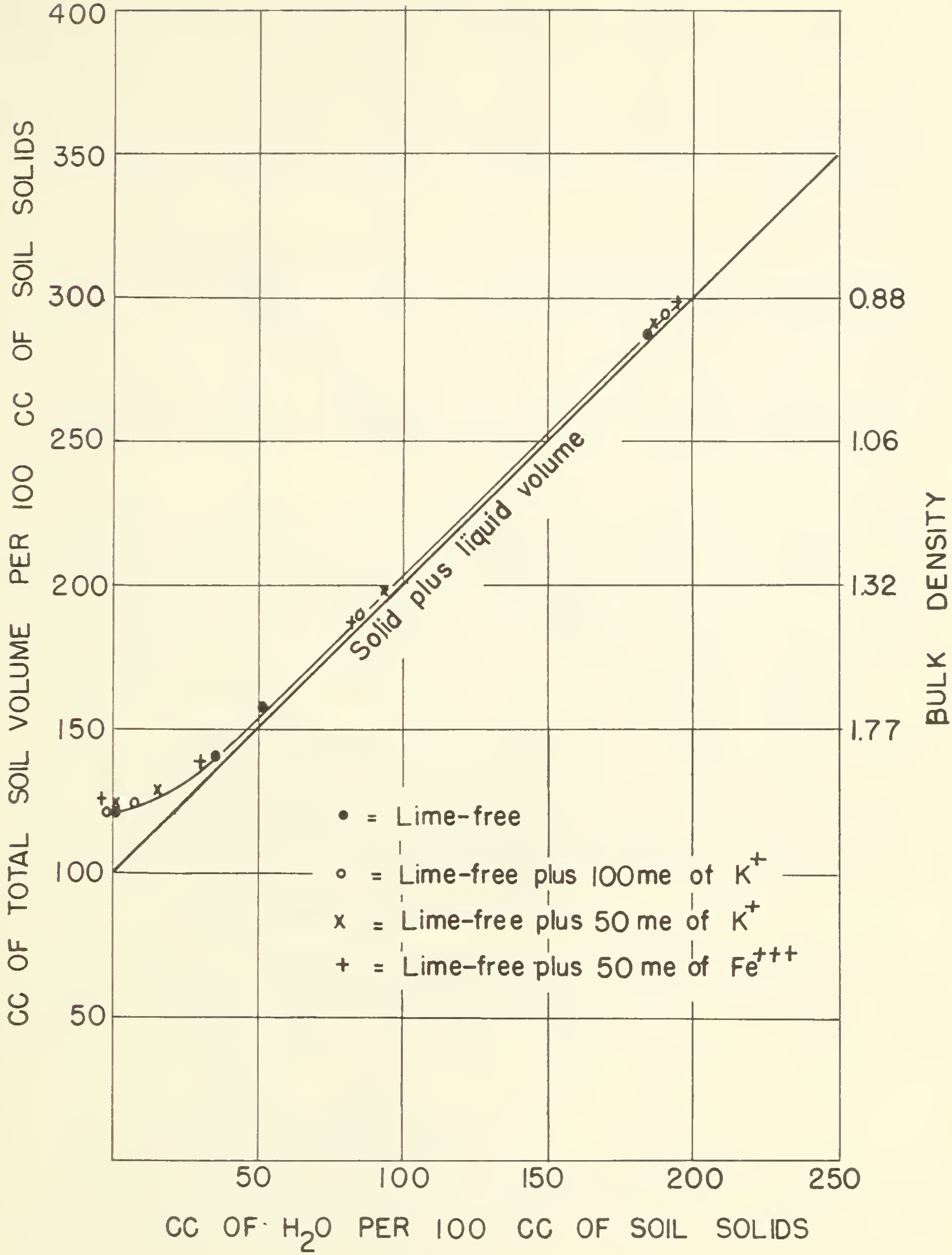

Figure 17.--Shrinkage curves for Houston Black clay, puddled lumps formed from cultivated surface soil.

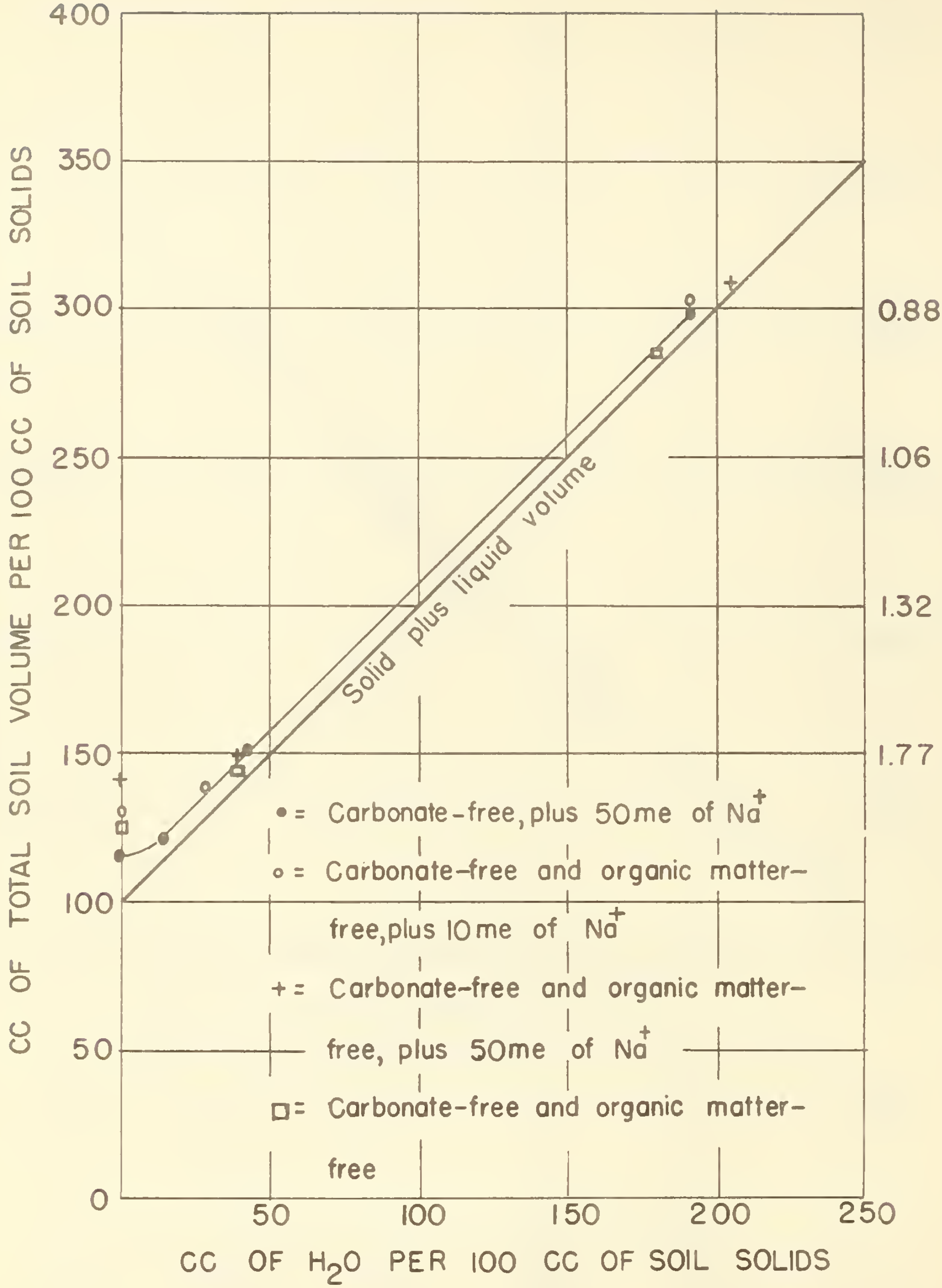

Figure 18.--Shrinkage curves for Houston Black clay, puddled lumps formed from cultivated surface soil.

lime-free clay without organic matter and with organic matter. These high values reflect the high water adsorption or swelling capacity of the clay separate. Oven-dry lumps showed volumes of 127 cc. without organic matter and 115 cc. with organic matter. As noted for the original soil, maximum density was greater or porosity less when the organic matter was present. Porosities at oven dryness were 21 percent without organic matter and 13 percent with organic matter. Minimum porosity was essentially the same for the 0.002-mm. clay as for the same Houston Black clay with about 40 percent of silt and fine sand included.

Laboratory Swelling, Slaking, and Water-Drop Effects

Figure 19 shows that Houston Black clay can be reswelled in the laboratory with only a very slight change in the porosity compared with that of original field samples. However, in some cases fragmentation occurs when reswelling is attempted, even when soil lumps are surrounded and held by sand on all sides. The presence of planes of weakness and the exact back-pressure of surrounding sand evidently are determining factors.

Starting with puddled, dried soil, water-drop slaking in the laboratory, described under "Experimental Materials and Methods," resulted in reconstituted lumps which were somewhat more porous than the original native-grass surface soil (figure 20). With eroded Austin soil, low in organic matter (figure 21), and with cultivated Houston Black clay (figure 22) a similar result was obtained. Repeated water-drop slaking caused only a slight change compared with a single water-drop treatment.

Figure 23 shows that slaking of air dried lumps by complete submersion in water resulted in soil with higher porosity than for the original, puddled lumps, especially at low moisture content, but lower porosity than for the natural soil before puddling. Relative to the porosity of puddled lumps, the increase in porosity by submersion was less than the increase from falling water drops (figures 20, 21, 22). Similar relationships have been noted with other samples.

Carbonate-free soil, puddled, dried, and slaked in excess water, showed shrinkage to lower porosity than the same soil with lime present, but otherwise handled in the same manner (figure 24). Air space was the same for both in the moist or wet range. Lime-free soil held more water at the maximum wetness determined.

Settling Volume and Moisture Tension

Settling volumes of soil in excess water, after stirring, are plotted on standard-type shrinkage curves in figures 25 and 26. Moisture retention values determined at several different tensions also are indicated on the shrinkage curves; in figure 27 they are plotted in the form of a moisture-tension curve. No attempt was made to measure gross volume of the soil mass formed by the soil used to determine moisture-tension values. Only moisture percentages were measured, in order to give some idea of the

(text continues on p. 40)

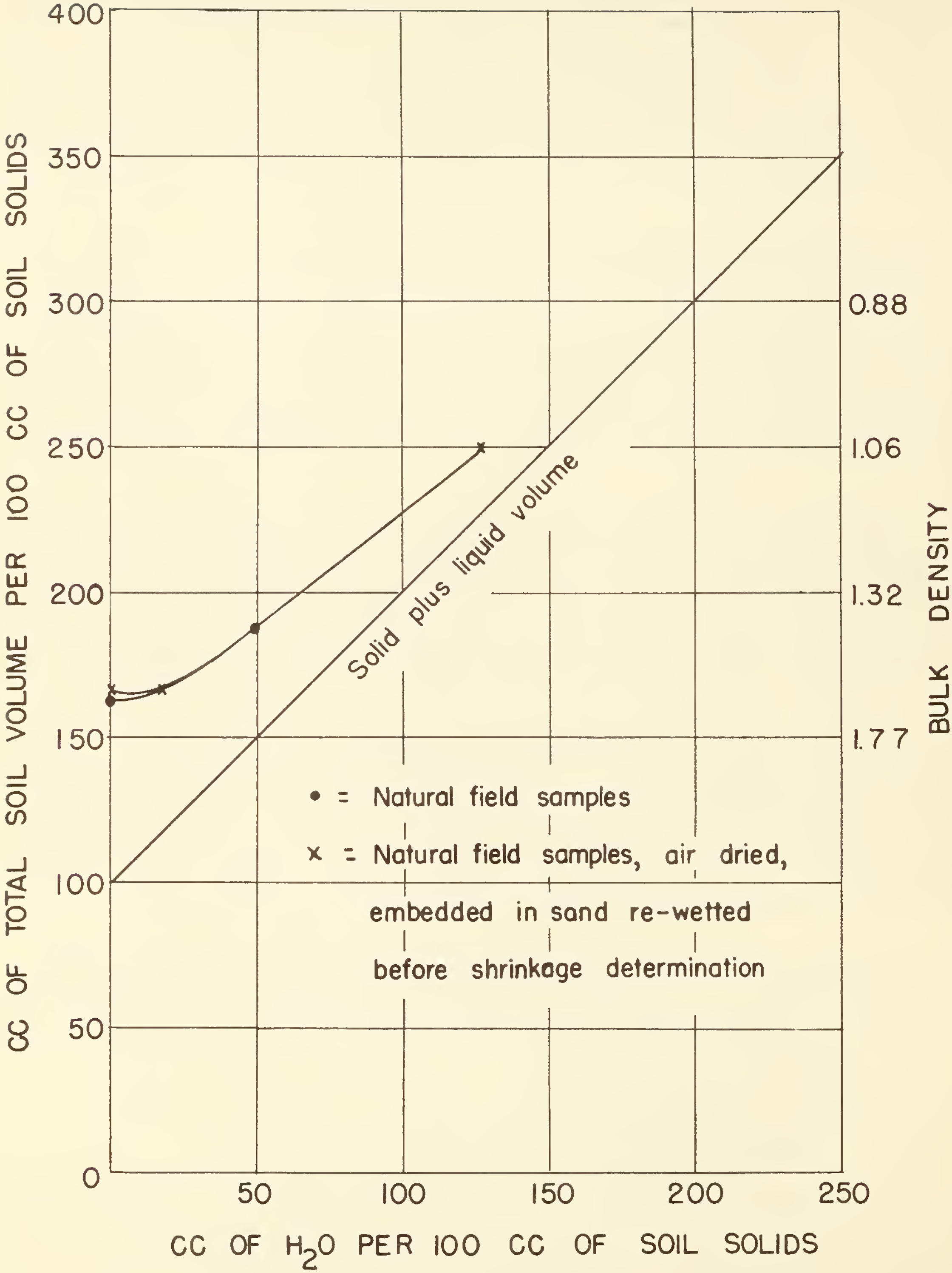

Figure 19.--Shrinkage curves for lumps of natural Houston Black clay, cultivated surface soil, plot 0-3, showing that reswelling of dry lumps embedded in sand had little effect on porosity.

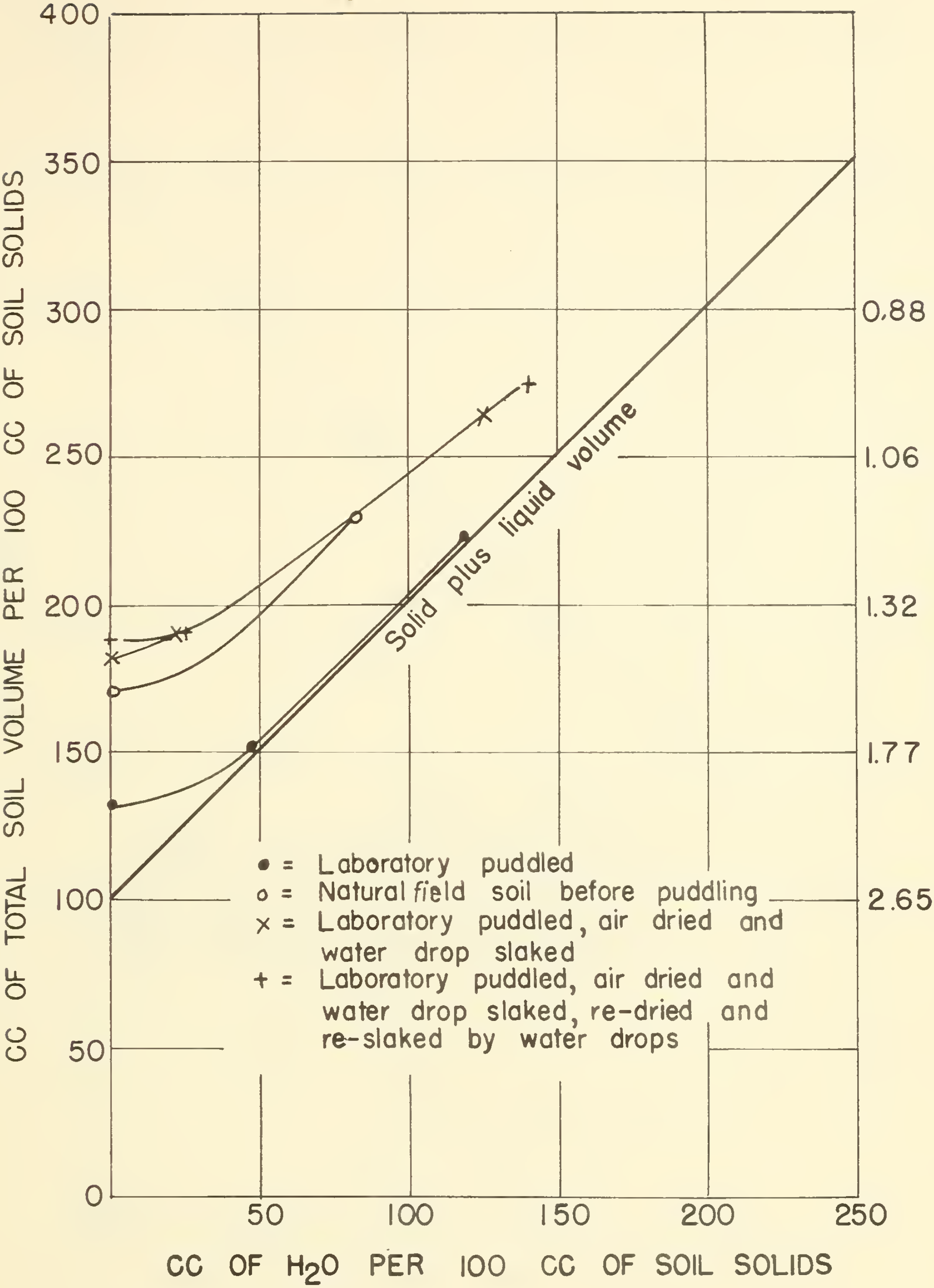

Figure 20.--Shrinkage curves for lumps of Houston Black clay, surface soil, native grass, showing the influence of water-drop slaking.

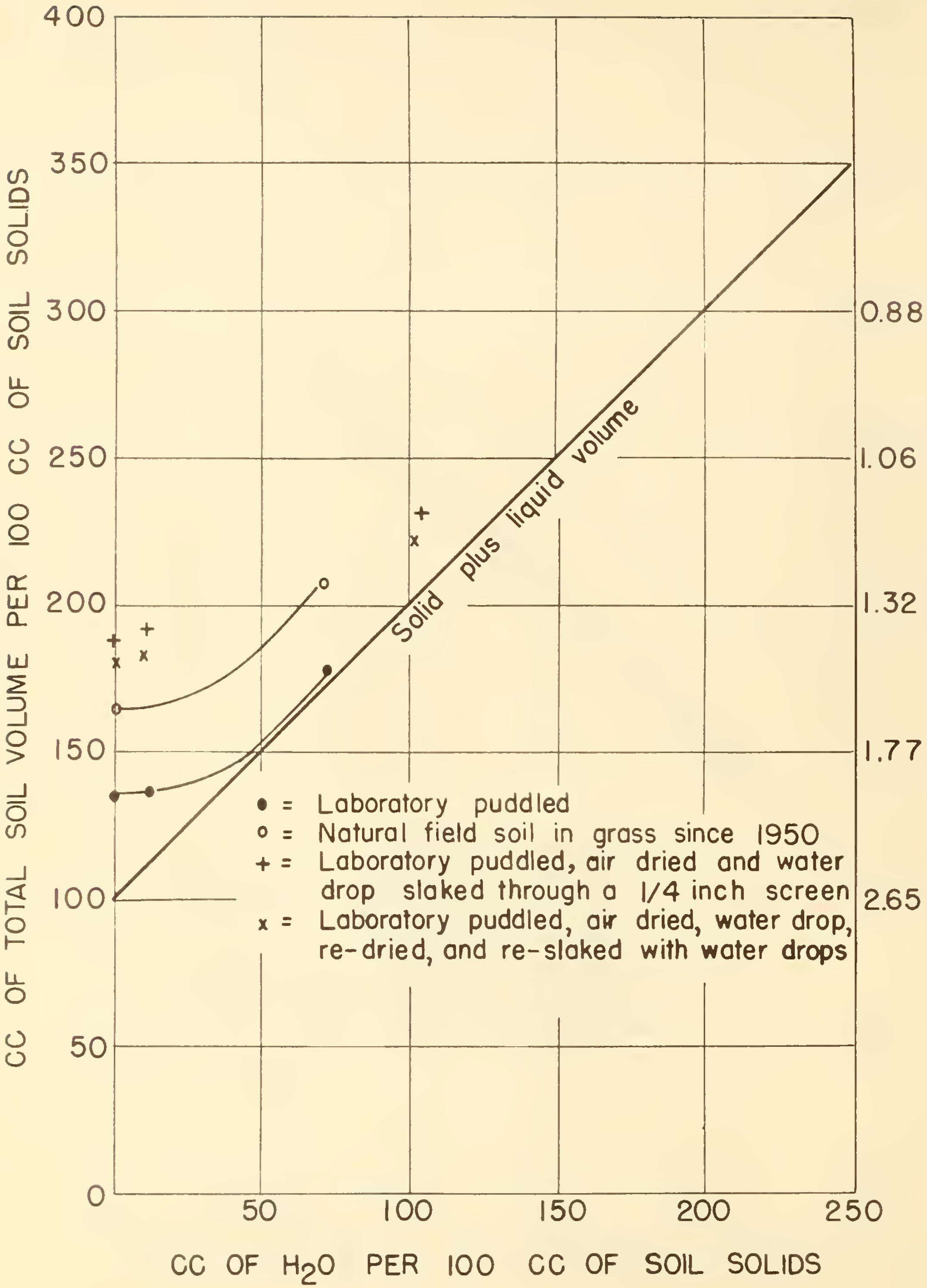

Figure 21.--Shrinkage curves for lumps of eroded Austin clay surface soil, showing the influence of water-drop slaking.

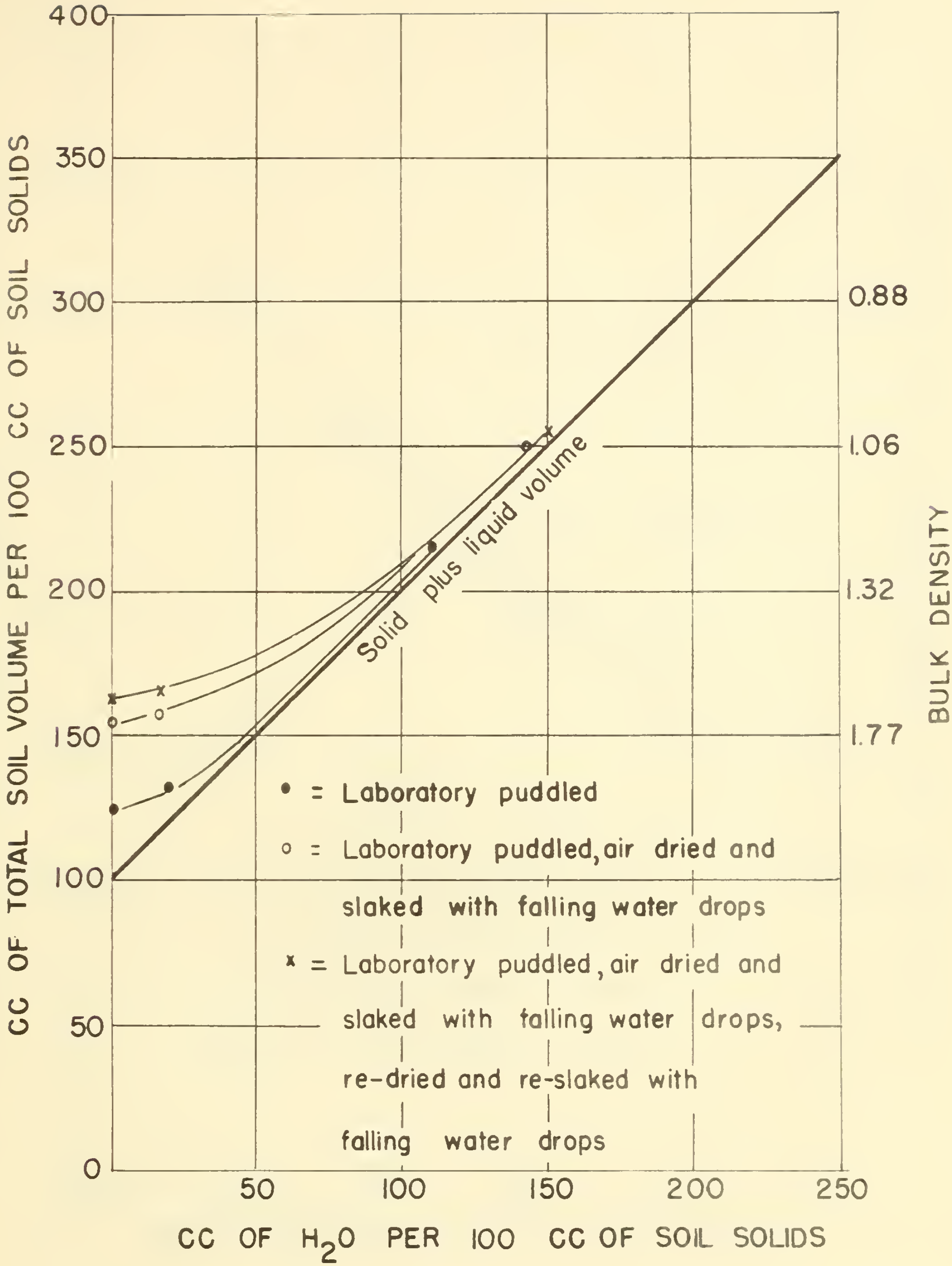

Figure 22.--Shrinkage curves for lumps of Houston Black clay, cultivated surface soil, plot P-2, showing the influence of water-drop slaking.

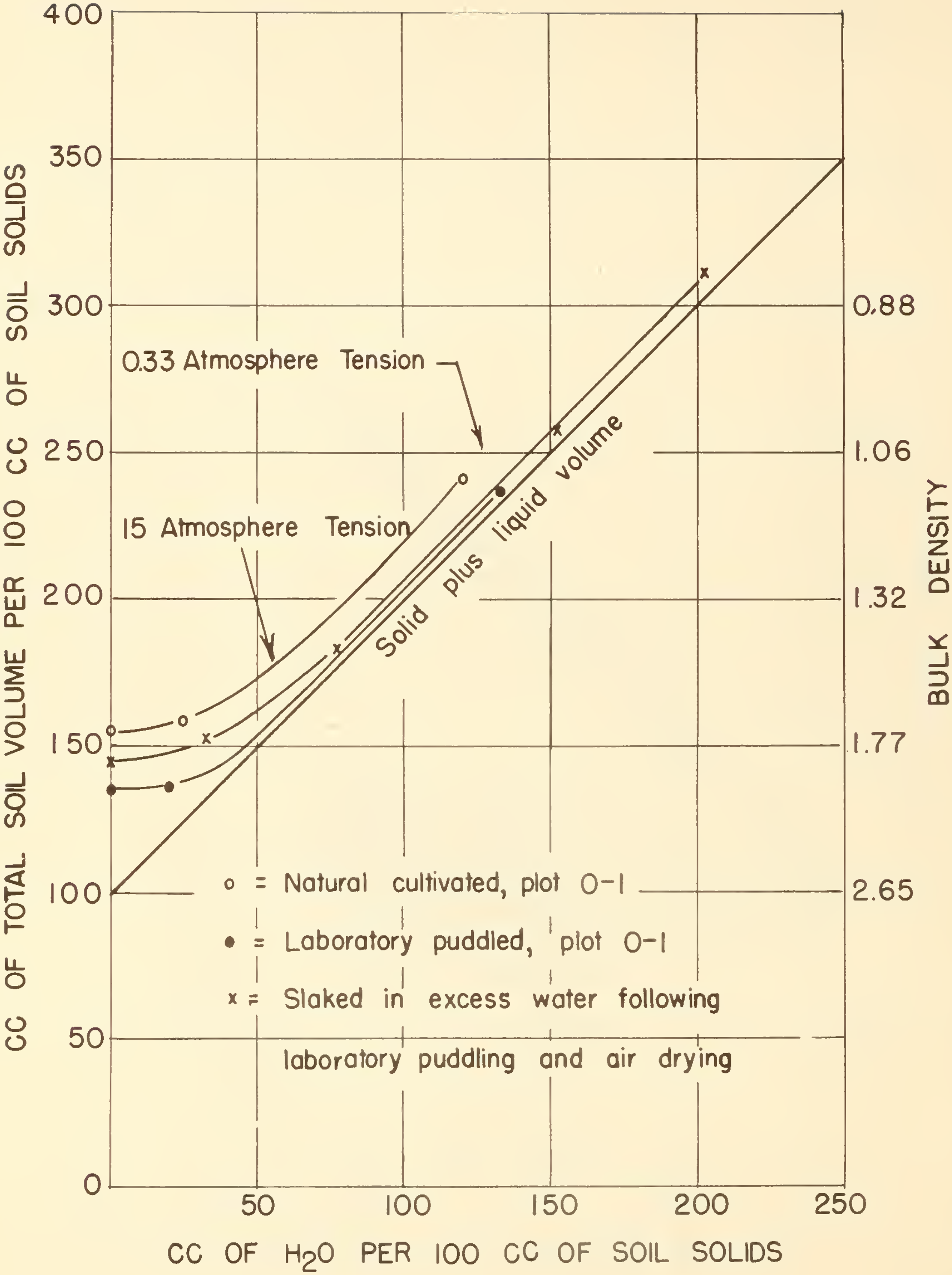

Figure 23.--Shrinkage curves for lumps of Houston Black clay, cultivated surface soil, plot 0-1: natural versus laboratory puddled versus slaked in excess water following laboratory puddling and air drying.

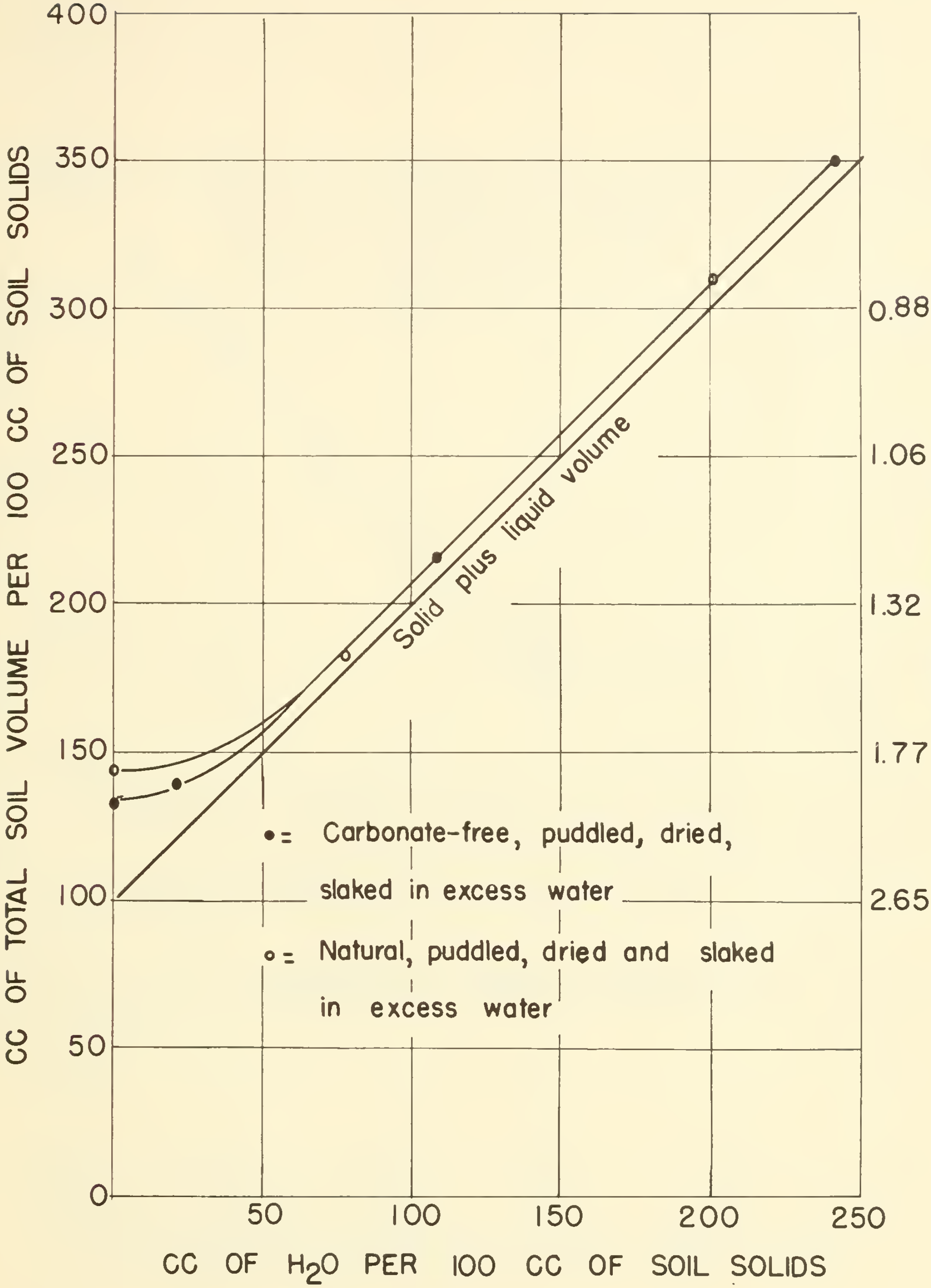

Figure 24.--Shrinkage curves for lumps of Houston Black clay formed by slaking dry lumps in excess water: carbonate-free versus puddled natural.

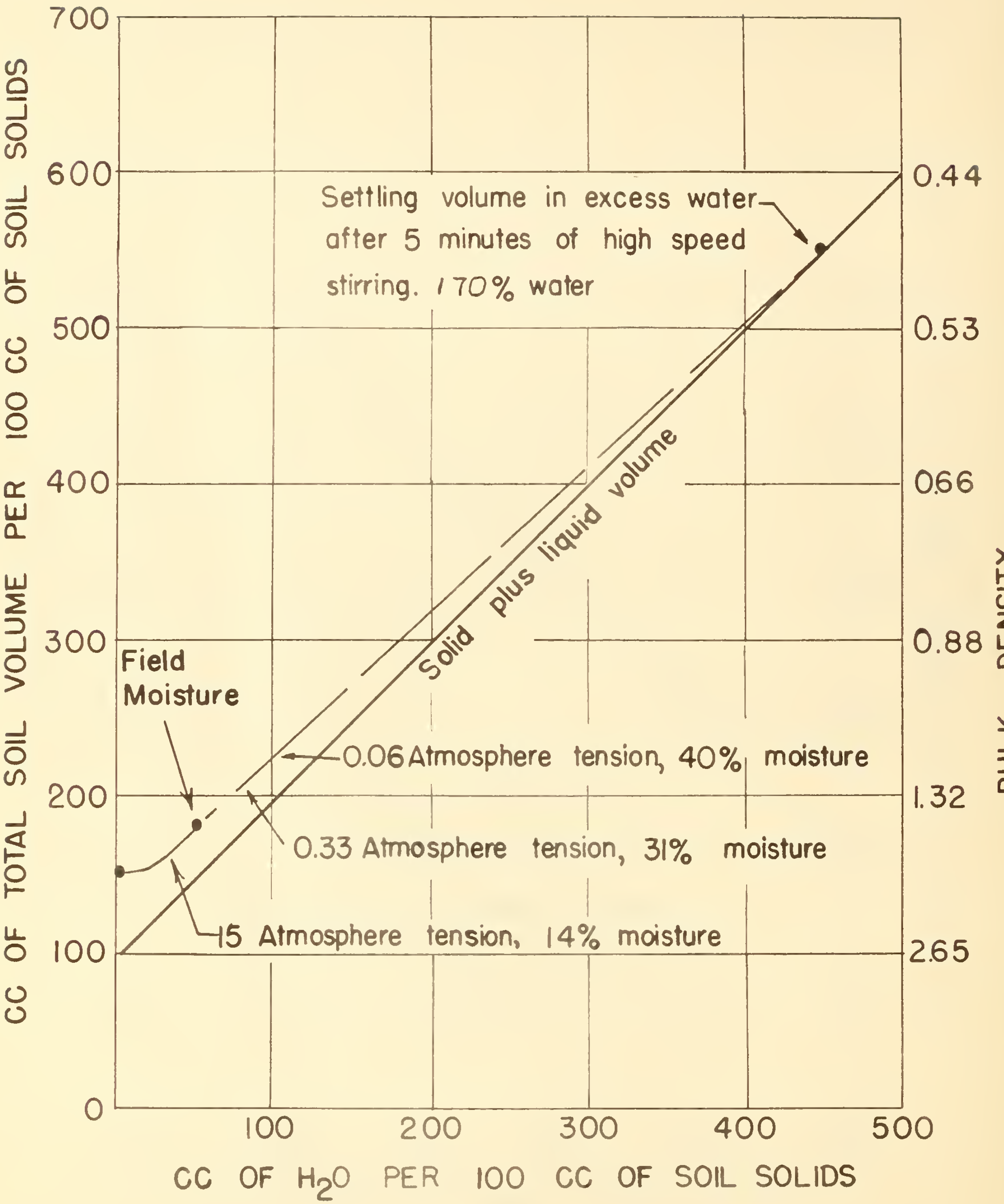

Figure 25.--Shrinkage curve for eroded Austin clay surface soil, Blackland Experiment Station. (Moisture at 3 tensions was determined on samples put through a 1/4-inch mesh screen. Volumes at field moisture and at oven dryness were determined on natural soil lumps.)

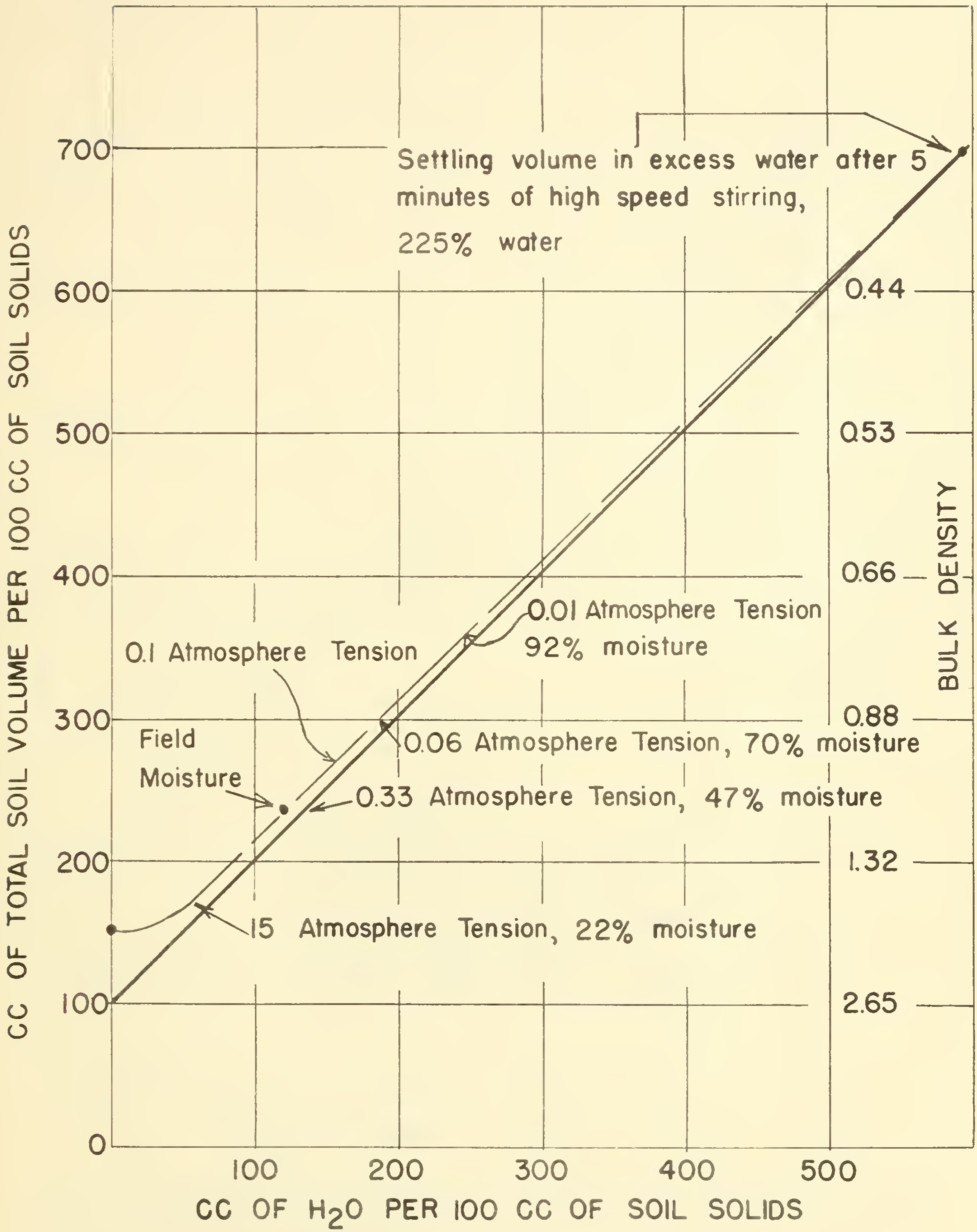

Figure 26.--Shrinkage curve for cultivated Houston Black clay surface soil, Blackland Experiment Station. (Moisture at 3 different tensions was determined on samples put through a 1/4-inch mesh screen. Volumes at field moisture and at oven dryness were determined on natural soil lumps.)

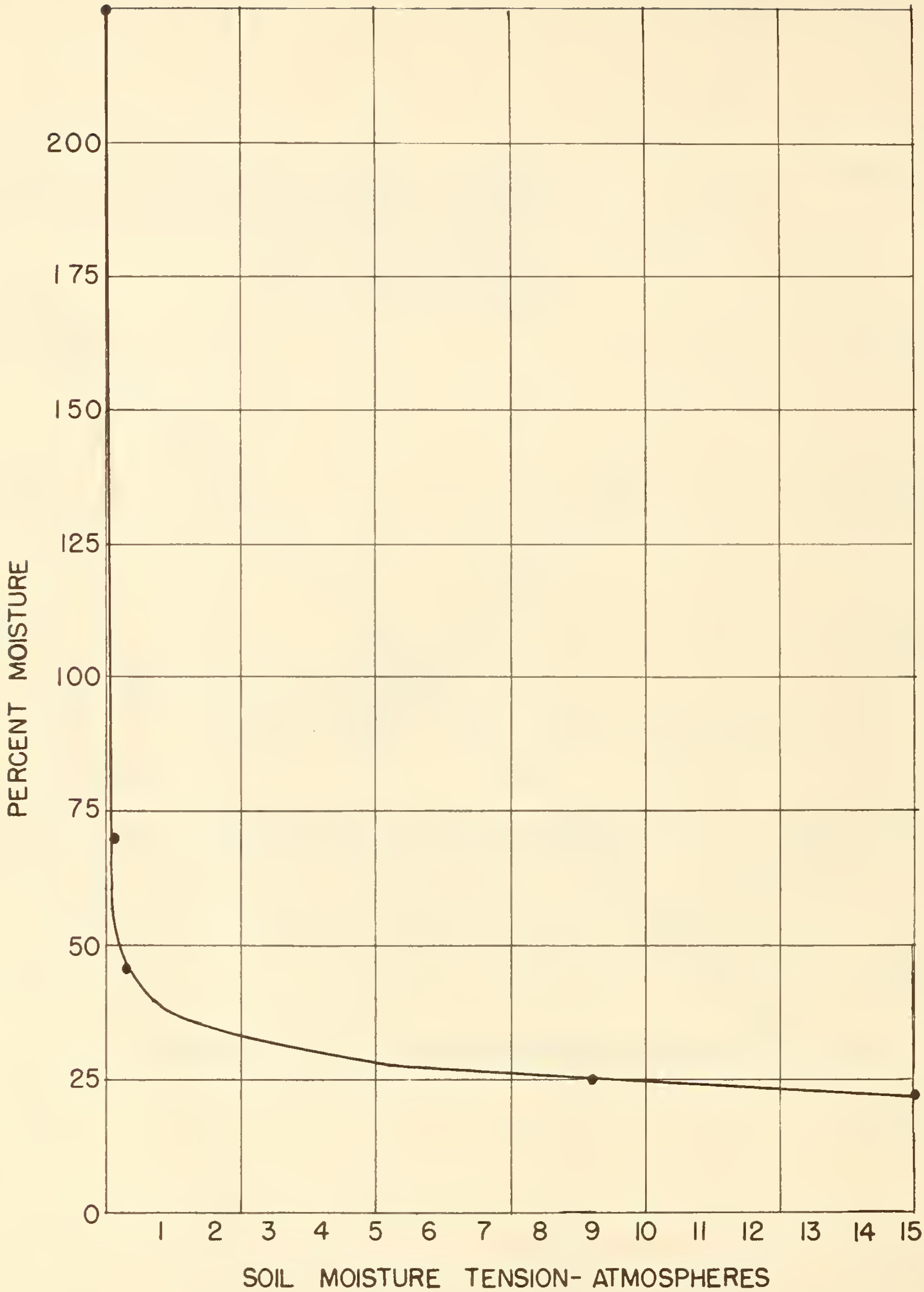

Figure 27.--Moisture retention to 15 atmospheres for cultivated Houston Black clay surface soil, Blackland Experiment Station. (The point shown as essentially zero tension was determined from settling volume after 5 minutes of high-speed stirring in water. Other points are for natural soil that was put through a 1/4-inch-mesh screen. The 0.06-atmosphere value was determined on a blotting-paper tension table, and the other points were obtained by air pressure in standard ceramic-base and visking-membrane equipment.

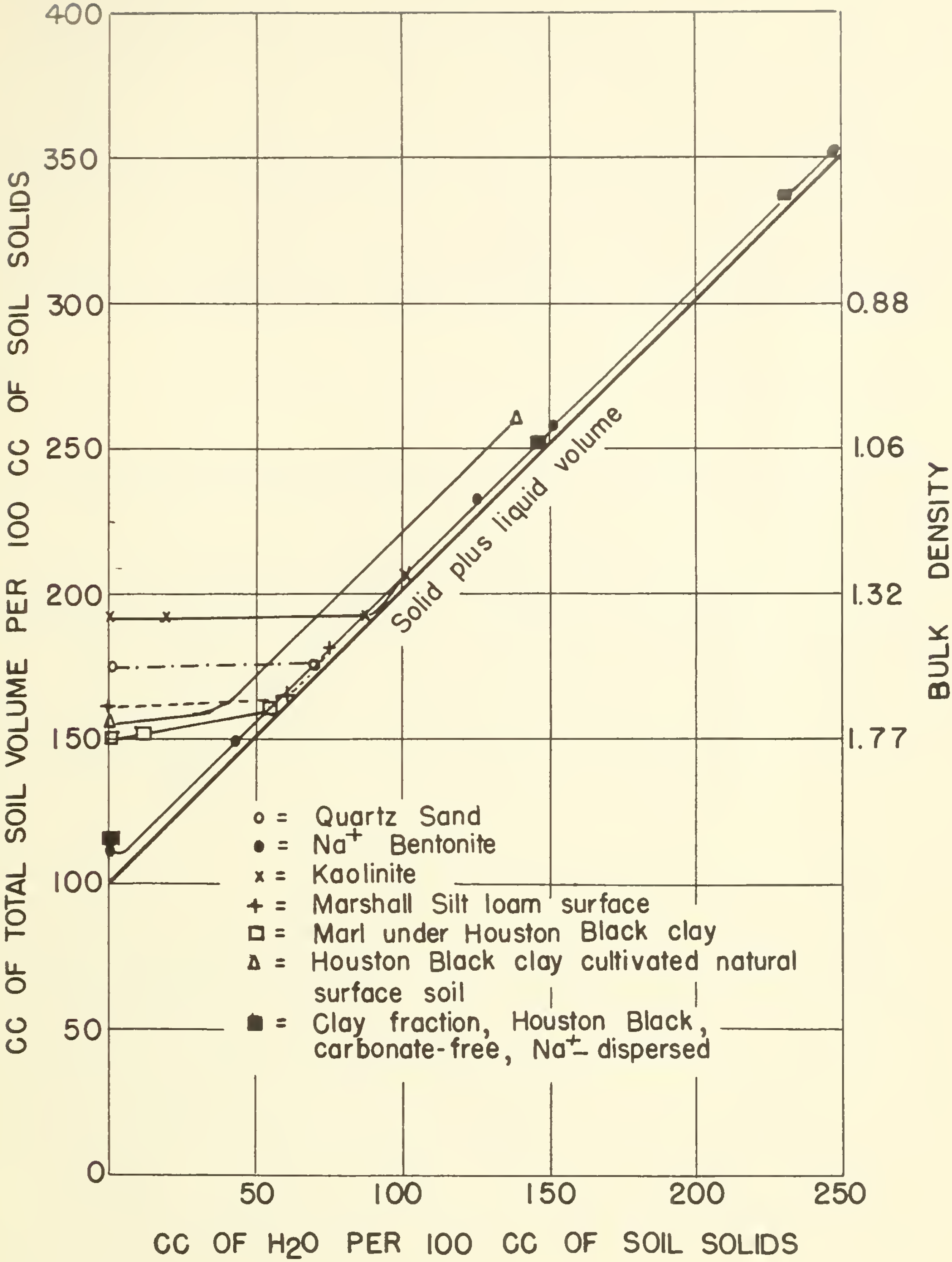

Figure 28.--Shrinkage curves for several different materials, as indicated.

tensions represented by different portions of the shrinkage curves. Volume determinations with other samples have indicated that the air space in loosely packed 1/4-inch-mesh soil is considerably higher than for most natural soil lumps, much the same as for lumps that are formed by water-drop slaking, previously described.

In comparison with shrinkage curves for soil lumps it is evident that mechanical stirring of soil results in the incorporation of a large quantity of water. Also, the retention of water by 1/4-inch-mesh soil that was soaked without stirring was much less at a low tension of 0.01 or 0.06 atmosphere than in the condition represented by settling volume. Retention at the 0.33 atmosphere tension, which is sometimes used as an index of field holding capacity, was considerably lower. Retention at a 15-atmosphere tension was above the range where shrinkage becomes small.

These curves illustrate relative features which have been consistent for the soils studied.

With soil samples treated with Na^+ or K^+ the clay remained in suspension indefinitely. In such cases the upper limit of swelling might be considered infinite.

The influence of simple mechanical variables of pretreatment on settling volume is illustrated by a comparison made with normal Houston Black clay surface soil. With natural air-dry soil poured into free water the settling volume was 1.85 cc. per gram; shaken end over end 20 times it was 1.80 cc. (this evidently eliminated some air pockets); with soil ground to pass a 2-mm. sieve, then poured into excess water, the settling volume was 1.92 cc.; with soil oven dried and poured into excess water, it was 2.59 cc.; with air-dry, soil stirred in water for 5 minutes with high speed stirrer, it was 2.66 cc.; and with air-dry soil stirred 10 minutes, it was 2.88 cc.

Clay Minerals, Silt, and Sand Comparisons

Shrinkage relationships of several materials are shown in figure 28. Sodium bentonite shows very high total shrinkage and minimum porosity at oven dryness. Commercial kaolinite showed highest porosity at oven dryness and limited shrinkage from saturation to dryness. Fine quartz sand showed no measurable volume change after settling in water in a graduate. Marl collected at a 6-foot depth under Blackland soil showed very slight shrinkage. Marshall silt loam surface soil from Missouri (Saline County) showed significant shrinkage, but slight compared with bentonite. Houston Black clay surface soil with good natural structure showed more air space at high moisture content than the other materials. It also showed more volume change or shrinkage, except for the bentonite and the separated clay fraction.

The highest moisture content shown for the bentonite was indefinite. In excess water, even without mechanical dispersion, sodium bentonite fills a very large volume. Cohesive forces are apparently small.

Lime-free 0.002-mm. clay, dispersed with Na^+, separated from Houston Black clay, showed greater total shrinkage than natural soil. Total porosity at oven dryness was higher than for Na^+ bentonite. Specific gravity of the clay by the pycnometer method was 2.60 compared with 2.38 for the bentonite. The maximum moisture determined for the clay was high compared with that of the original soil, but the absolute value lacks definite significance: it reflects the moisture content at which lumps can be formed without excessive stickiness. The same is true for the bentonite. When the bentonite was drained under low tension after soaking in free water, it retained 1,046 percent water at 0.1 atmosphere, 742 percent at 0.33 atmosphere, and 646 percent at 1.0 atmosphere. The lime-free soil clay separate dispersed with Na^+ held 270 percent moisture at the 0.1 atmosphere, 228 percent at 0.33 atmosphere, and 160 percent at 1.0 atmosphere of tension.

DISCUSSION OF RESULTS

It seems necessary to give major consideration to shrinkage and swelling in studies of Blackland soil physical properties. The total effect of this factor is complex and difficult to evaluate. Under field conditions the entire soil mass to depths of several feet varies widely in volume, porosity, and hardness, depending on moisture content. shrinkage cracks are a normal feature of soil profiles. Surface cracking may begin in less than 24 hours after a rain and deep cracks occur during long dry seasons. Cultivation and rain tend to cover cracks but may not eliminate them entirely. Soil that falls or washes into cracks is naturally loose, probably similar to lumps that are slaked by falling water drops in the laboratory. Variations in natural soil character, history, management, and weather account for the occurrence of many different crack patterns and characteristics similar to those classified by Hardy and Derraugh (8). Rate of drying is an important factor to consider, as well as amount of drying. Crack patterns caused by mechanical treatment as compared with natural cracking are shown in Figure 1.

Soil lumps or clods studied in the laboratory may approximate the different states of soil that occur under natural conditions. However, at best, the information obtained from such samples is only one aspect of natural situations which occur in the field. Arrangement of these various soil units with respect to each other, and in relation to cracks, plants, and weather sequences, accounts for field behavior. Even so, it is important to attempt to understand the reactions of soil lumps or clods as units to provide a basis for the development of new and clearer concepts of what to expect when the influences of several factors are combined.

It has been shown that montmorillonite is the predominant clay mineral in Houston Black clay (14) and, presumably, in other Blackland clay soils. This might be interpreted as suggesting that shrinkage and swelling are accounted for by interlayer water. Yet the data presented show that gross shrinkage and swelling is small or insignificant at low soil moisture contents. Soil porosity or density often is essentially equal at air

dryness and at oven dryness. Air dryness normally represents equilibrium with atmospheric relative humidity of 60 percent or higher. Barshad (1) has stated that the interlayer water of montmorillonite is satisfied by a relative humidity of 50 or 60 percent, which would be at least as dry as normal air dryness. A somewhat higher moisture level of 90 percent relative humidity or less was cited by Page (24) as providing for full swelling of montmorillonite to the 20 Å spacing. This would be air dryness under humid conditions and well below the 15-atmosphere percentage. It would be close to the range within which gross shrinkage ceases. From the viewpoint of soil structure and gross shrinkage, therefore, it appears that interlayer water within an "expanding lattice" of about 20 Å spacing between layers is an inadequate basis for explaining the major shrinkage and swelling normally found for soils of the Blackland area.

The concept that interlayer and interparticle water may not be distinctly different and that expansion may continue until the particles become essentially unit crystals of about 1 millimicron in thickness is consistent with observed results. If swelling is viewed as an osmotic property of clays, the expansion of unit crystals into an infinite volume of water may be limited only by attractive forces between particles or by cementing or binding substances. Kelley (13) has pointed out that in considering swelling as an osmotic property it must be recognized that swelling is not directly proportional to exchange capacity. This and other complexities in predicting or explaining swelling might be easier to understand in terms of the cohesive forces that oppose the osmotic forces of swelling, rather than as limits to the swelling tendency itself. In terms of structure, the maximum swelling volume obtained by any procedure seems to depend upon the same cohesive forces that determine structure. As these cohesive forces are weakened, mechanically or chemically, the swelling volume increases. Settling volume in excess water provides a measure of "free swelling," as used by Foster (5) in studies of different varieties of bentonite. She noted that the pretreatment and rate of addition of the dry clay to the water must be standard in order to obtain valid comparisons. In the present studies, a pretreatment of 5 minutes of high speed stirring has been used to prepare soil or clay for determination of settling volume. This treatment seems to minimize the effect of previous steps in handling samples, which are difficult to standardize. Moreover, such treatment, though arbitrary, is believed to be somewhat comparable with the extreme state of bare, wet surface soil in the field when subjected to intense rainfall.

It is clear that measurement of settling volume in excess water depends upon flocculation or cohesion among fine clay particles. When dispersion is maintained by treatment with Na^+ or other dispersing cations, the clay appears to occupy an unlimited volume.

Mattson indicated that the upper limit of swelling with a sodium bentonite corresponded with a tension of 0.02 atmosphere (21). It is not apparent in the present studies that an upper limit of swelling can be established in terms of tension or otherwise, unless some definite structure or arbitrary procedure is specified. Large differences in the amount

of water associated with soil or clay at very low tensions are caused by changes in procedure or structure. As an example, Winterkorn and Baver (30) reported that gross swelling of montmorillonite was larger with gels formed from suspensions than with gels formed from the dried clay. With Houston Black clay surface soil the settling volume as a measure of swelling varied from 1.85 to 2.88 cc. per gram depending on the mechanical procedure of dispersion used with the air-dry soil.

The results presented illustrate the strong influence of mechanical factors on structure of fine-textured soils. Simple compaction or puddling in the field or laboratory may eliminate essentially all air space in a wet soil mass, even with virgin surface soil containing more than 5 percent organic matter. Moreover, typical shrinkage during drying merely results in reduced volume of unit masses, whose size and shape is determined by structure, until the tension is considerably greater than 15 atmospheres. No appreciable amount of air enters the units until shrinkage per unit of water loss begins to become small. This point or range is recognized as the end of normal shrinkage or the beginning of residual shrinkage. In working with molded blocks of clay soils Holmes (10) found this point to correspond with a p^F of about 5.

It has been suggested (15) that the moisture lost during residual shrinkage may correspond with interlayer water of the clay. However, in the present study minimum residual shrinkage was found with sodium bentonite or lime-free, sodium-treated clay. These are the systems in which interlayer water might be expected to be greater than in soils with diluting substances and strong macrostructure.

A tendency for larger particles to form an increasingly complete and rigid framework as drying progresses is believed to be a more logical explanation of the incidence of residual shrinkage than any definite relation to interlayer water.

Soil lumps formed by water-drop slaking and low-tension drainage in the laboratory have been among the samples with highest porosity and air space. Evidently these loosely packed units have permitted some water loss in the moist or wet range without corresponding volume reduction. In other words, there was no overall normal shrinkage. The lump or mass was not coherent enough to shrink as a unit. This is the condition commonly visualized for natural soil. In fact, one surprising result in this work has been the tendency of natural soil units or lumps to exhibit essentially normal shrinkage over a very wide moisture range, even lumps of virgin soil having strong aggregation. Extreme looseness of packing of aggregates evidently is required before aggregates shrink individually, providing additional air space within lumps. This suggests a dominance of the cohesive forces within the clay.

The openings which develop under field conditions as a result of shrinkage are more like continuous cleavage planes along positions of

weakness than they are like specific aggregate surfaces. One cause for the position of weakness, as suggested by Johnston and Hill (11), may be moisture. When young crops in rows draw most of their moisture from a limited distance, the first soil cracks may be caused to form midway between rows, where moisture content is highest and cohesion is therefore weakest. At the same time, it should be noted that maximum soil puddling and compaction also occur midway between rows where tractor wheel pressures are applied, repeatedly. This action eliminates air space and tends to create massive structure. The size of blocks of soil that function as a unit is thus increased. From all evidences at hand, this should result in larger shrinkage cracks at wider spacings, which appears to be typical of intensively cultivated, clean tilled row crop land.

Sodium treatment increased the maximum dry density of Houston Black clay soil with organic matter present, but failed to increase and even seemed to decrease the maximum dry density after organic matter was removed. It has been assumed that increased density following sodium treatment could be explained as more perfect orientation of the plate-shaped clay particles. The same reasoning might apply to the slightly increased densities found associated with lime removal and organic matter removal. However, the failure of sodium to show the same tendency with organic matter removed is not explained. Some information is available on interactions between organic matter fractions and montmorillonite, but the present results are not completely explained (4). The subject needs further investigation.

Treatment of lime-free soil with ferric sulfate, and with potassium, as bicarbonate, failed to cause any definite changes in shrinkage curves or maximum density, although dispersion with the K^+ was essentially as definite as with Na^+. This suggests some possible relationship to the results of Baver and Winterkorn (2) showing that in the uptake of water and swelling the K-Putnam and other K^+ clays studied behaved more like H^+ or Ca^{++} systems than like Na^+ or Li^+ clays. On the other hand, with commercial bentonite the different exchangeable cations had little influence.

It appears that before the results obtained to date can be fully explained studies are needed of methods for determining more about the orientation of clay particles following various treatments.

Among the soils studied, Houston Black clay and the samples from the Gulf Coast Prairie have been found similar in structure except where natural sodium influences were noted in the Gulf Coast samples. Austin clay has shown somewhat less total shrinkage, which might be explained on the basis of less clay. A commercial kaolinite and a Marshall silt loam from Missouri showed much less shrinkage, but the volume change of both was great enough that it might be significant in soils studies. The bulk density of the Marshall changed from 1.48 when wet to 1.66 when oven dry.

Sodium bentonite showed more total volume change and less porosity when dry than any soil. When 0.002-mm. clay was separated from lime-free, sodium-treated Houston Black clay, the minimum porosity by the Varsol[8] method was 13 percent compared with 8 percent for the bentonite. When porosity of dry bentonite was calculated from bulk density by paraffin coating the average value was 11 percent. No upper limit of swelling was established with either because they seemed capable of occupying extremely large, possibly unlimited volumes. At a moisture tension of 0.33 atmosphere free-swelling bentonite held 742 percent moisture by weight and the 0.002-m., lime-free, sodium-treated clay held 228 percent. Lime-free Houston Black clay soil with 50 m. e. of Na^+ per 100 grams of soil held 134 percent moisture at the same tension.

Two extreme physical conditions might be indicated by this study, as follows: (a) Puddled sodium bentonite or puddled lime-free sodium clay from Houston Black clay, and (b) natural Houston Black clay surface soil in a loosely packed condition. The major treatments involved in reducing loose Houston Black clay to the extreme represented by the sodium clay seem to include: (a) Mechanical packing or mixing, (b) removal of free lime, (c) removal of textural particles coarser than clay, and (d) dispersion with exchangeable Na^+. Conversely, the reverse steps appear to be: (a) Replacement of exchangeable Na^+ with Ca^{++} (H^+ might be equally effective) to cause flocculation, (b) dilution of the clay with an approximately equal part of silt and fine sand, (c) dilution of the system further with finely divided lime, (d) forming the mass into loosely packed, separate aggregates by mechanical means. In nature, these mechanical means include differential wetting and drying, temperature changes, freezing and thawing, earthworm castings, ant and other small animal workings, and tillage followed by gravity settling under the influence of the various natural factors. Under grassland conditions the influence of earthworms and other small animals appears to be of considerable significance. Under intensive cultivation, soil loosening by tillage followed by gravity settling of particles loosened by differential wetting and drying, constitutes a major cycle of structural change which seems to account for common conditions observed in the field.

In the processes described it is clear that plants are one factor accounting for differential drying. It is also known that plant roots penetrate deeply in this area (commonly 5 feet or more with cultivated plants as well as with many perennials). These root openings are sometimes credited with mechanically increasing soil porosity. It is obvious that raw organic matter from roots or from above-ground plant parts may separate soil aggregates mechanically. Microbial products and soil organic matter are expected to have less obvious functions such as binding clay particles into more water-stable units and reducing the stickiness between soil units (22). When aggregates are of a favorable size this influence of organic matter is desirable. In the case of large, puddled blocks the presence of organic matter may provide some undesirable water stability. It appears that pure clay blocks or lumps,

8/ See footnote 5.

as studied, are more likely to break down during shrinkage and swelling than lumps containing organic matter. Bentonite lumps invariably shatter into rather small fragments during drying or under variable humidity. Clay soils remain intact in larger units, especially when considerable organic matter is present.

These functions of organic materials probably are active in Houston Black clay and in similar soils, but results of the present study show that simple mechanical packing or mixing can force moist or wet aggregates into a coherent mass having very little air space. All of the raw and decomposed organic matter of native grassland does not prevent such a mass from holding together and shrinking as unit blocks which are much larger than desired soil aggregates. Reconstitution into separate macroaggregates of desirable size (roughly from 1 to 10 mm.) seems to be a mechanical process, as already described. If any large, dense soil block is buried below tillage depth and is held firmly on all sides by surrounding soil in cultivated land, the factors that cause looser soil and distinct aggregates may not modify the block for long periods. As shown in the laboratory, shrinkage followed by reswelling and by reshrinking may be accomplished without altering the density or porosity. However, laboratory results also emphasize that fracturing and collapse into smaller units is a tendency which dominates during repeated wetting and drying unless units are firmly held on all sides. The same reactions occur in the field. When cracks form in the field beside a dense block, wetting and drying cycles loosen fragments of the block and these fall into cracks and may remain loosely packed.

A primary function of roots in breaking up dense soil blocks in this area appears to be related to differential drying and rewetting. Earthworm and other small animal activity forms soil into mechanical units considered to be of desirable aggregate size. This process is not necessarily related to shrinkage and swelling.

The marl parent material from which Houston Black clay is derived on the Blackland Experiment Station showed only slight shrinkage from near saturation to oven dryness. There was no tendency toward a range of normal shrinkage. Presumably, the marl has a semirigid framework of calcium carbonate which prevents a sample from swelling and shrinking as a mass. The porosity of the marl at oven dryness was greater than that of dry Houston Black clay subsoil. When wet and swollen the porosity of the subsoil usually is greater. Repeated wetting and drying tends to shatter marl into fine fragments. These fragments are recognizable in the lower subsoil; in the surface or upper subsoil, however, such fragments usually are absent. There seems to be little evidence of lime cementation in the soil profile inherited from the parent marl. Lime cementation occurring in the upper subsoil appears to be secondary in the form of concretions (29). Aggregate formation and stability show no apparent relation to lime as a cement. The shrinkage-swelling studies show no influence of the lime except dilution of the clay and a slight tendency to reduce the maximum density.

When fragments or aggregates form by differential wetting and drying or by other means and settle only by gravity, these aggregates may remain distinct and easy to separate for long periods of time. More work is needed in order to understand why these units sometimes remain intact rather than recombining into a massive state. Prolonged wetness appears to favor recombination of the soil into large blocks that are essentially massive. The present work shows that it is simple to compact or to puddle wet aggregages into a mass with small interparticle distances which is practically air-free and which shrinks as a unit. The stabilizing factors opposing this seem to be rather small in magnitude.

Orientation of clay plates within aggregates might increase density and alter stability. Peterson (25) has indicated that strength and cementation by clay films is greatest with dispersed clay. With Houston Black clay soil the clay is flocculated; particle orientation would seem less likely than with dispersed clay.

Platy structures were found by Peterson (26) to be characteristic of pure kaolinite, whereas a predominance of montmorillonite resulted in cubical units. In Blackland soils the cubical tendency seems definite except in some platy layers near the surface, believed to be caused by compaction or puddling. The absence, in most cases, of any visible platy structure raises some doubts as to whether the clay plates of montmorillonite are readily oriented. However, it is difficult to visualize the extremely low porosities measured without believing that considerable orientation occurs. This question needs further study by techniques which can evaluate degrees or orientation.

SUMMARY AND CONCLUSIONS

Shrinkage studies have been carried out with natural and with artificially formed soil lumps or clods of Houston Black clay, Austin clay, and a few other soils and materials. Maximum bulk density and minimum porosity are found with dry soil. There is little or no difference between the density at oven dryness and at air dryness or slightly higher moisture. From near the sticky point (low tension of about 1/3 atmosphere) to drier than the 15-atmosphere tension, Blackland soil volume tends to change almost 1 unit for every unit of water loss. This is true for natural soil containing considerable air as well as for puddled lumps that contain no air. Thus, water loss by drying or by increased tension may not increase the air content of soil lumps or clods until the lumps are at moisture contents below the available range. Only loosely packed aggregates, such as those formed by waterdrop slaking and gravity settling in the laboratory, show appreciable drainage under tension without an equivalent decrease in volume.

Natural soil profiles studied in the Blackland Prairie, Gulf Coast Prairie, and Reddish Prairie of Texas show a consistent tendency for increasing bulk density and decreasing porosity with depth, at least in the upper profile. Severely packed or puddled soil layers at or near the surface may be recognized because of their equal or greater density compared with layers immediately below. In order to make such comparisons it is essential that moisture contents be comparable. Otherwise, the driest, most shrunken sample will be densest, regardless of structure.

The moisture held by soil at very low tensions has proved to be dependent on procedure or structure to such an extent that an upper limit of swelling is difficult to define. Settling volume of soil in excess water following vigorous mechanical stirring is suggested as a measurement of some interest which may serve as a practical upper limit of free-swelling that may be similar to the extreme state under intense rainfall in the field. However, in the case of lime-free soil or clay dispersed with Na^+ and mechanical stirring no upper limit is recognized because the colloidal particles stay in suspension in large volumes of water. This is consistent with the concept that swelling may be visualized as an osmotic phenomenon that leads to infinite expansion unless opposed by attractive forces between clay particles.

Interlayer water of montmorillonite clay is inadequate to explain the gross swelling and shrinkage of soils or clays studied, because only a very small part of the total volume change occurs at moisture levels that provide for the interlayer water necessary to cause expansion of the layers to a full 20 Å spacing. The concept that there is no clear distinction between interlayer and interparticle water is consistent with results obtained.

Residual shrinkage extends over a wider moisture range with natural soil than with bentonite or clay separates. This suggests that the establishment of a partial framework of solid particles prevents normal shrinkage and results in a change to residual shrinkage. Interlayer water does not seem to explain the incidence of residual shrinkage.

Starting with moist or wet Houston Black clay surface soil, thorough puddling or packing eliminates practically all air space, even with virgin soil that is high in organic matter. Essentially normal shrinkage then occurs down to about 10 percent moisture. Maximum density in the dry state is about 2.0 gm. per cubic centimeter, and minimum porosity is 25 percent. Lime removal and organic matter removal result in slightly lower porosities. Treatment of lime-free soil with Fe^{+++} and with K^+ had no effect. Exchangeable Na^+ resulted in increased dry density to about 2.25 gm. per cubic centimeter, or porosity of 15 percent when organic matter was present; with organic matter removed the maximum density was less. When 0.002 mm.-clay was dispersed with Na^+ and separated, the maximum density of molded lumps after drying was 2.30 gm. per cubic centimeter, and porosity was 13 percent with organic matter present; but with organic matter removed the minimum porosity was 21 percent. Wyoming bentonite porosity of molded lumps was 8 percent at oven dryness.

Shrinkage cracks in the field are believed to form where soil cohesion is weakest. This may mean where the moisture content is highest, as midway between rows of cultivated crops. However, structure has a strong influence on the size of units between shrinkage cracks. In general, a dense soil shrinks in large units. The formation of loosely packed aggregates from dense or massive soil is believed to be caused primarily by differential shrinkage and swelling with moisture changes. Plant roots, especially in grassland, account for considerable differential drying and rewetting. Earthworms and other small animals appear to have originated many of the surface soil aggregates in grassland. In cultivated land differential shrinkage and swelling appear to be the dominant factor in the fracturing of large blocks of soil, lifted or turned up by plowing, into fragments or aggregates of suitable size for seedbeds and for proper cultivation. Changes in relative humidity and perhaps temperature may cause considerable fragmentation of large soil units, even without rain. Surface soil organic matter may contribute to the stability of aggregates favorable for seedbeds after the aggregates are formed by differential shrinkage and swelling or by earthworms or other animals. Organic matter also may sometimes increase the water stability of large lumps or blocks of soil to an undesirable extent.

An understanding of the behavior of individual soil lumps is recognized as only one aspect of the total soil structural condition as expressed under natural field conditions. However, it appears that studies of soil lumps offer some opportunities for clarification of the interrelated effects of basic factors such as clay orientation, cations, and organic matter, together with mechanical influences. At the same time, it may be possible to use information about soil lumps or clods to interpret the effects of various field practices or treatments, and to predict the results of new combinations of conditions and procedures.

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